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AN INVESTIGATION OF THE AREAL AND DYNAMIC PROPERTIES OF RAINFALL AND ITS INFLUENCE ON RUNOFF GENERATING PROCESSES

Janusz Niemczynowicz



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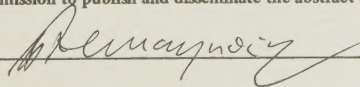
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Abstract The work presents an analysis of the areal and dynamic properties of short-term rainfall. The studies reported in this work are based on measurements of rainfall made on a network of 12 gauges situated in the city of Lund, Sweden. On the basis of 3-year series of 1-minute rainfall records it was shown that both areal and dynamic properties of rainfall influence the shape of runoff hydrograph and the peak flow discharge. The probability that a certain rainfall intensity will occur as an areal value is lower than the probability that the same intensity will occur as a point value. Areal intensity-duration-frequency relationships and statistical areal reduction factors were developed for the city of Lund. Rainfall movement characteristics were derived from point measurements in 12 gauges and were used for determination of the possible range of the influence of rainfall movement on peak flow discharge from real catchments in Lund. The directional bias on peak flow discharge was quantified in a statistical terms. The results that have been presented entail vital practical implications with regard to the choice of rainfall input for modeling of runoff.				
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RAINFALL AND ITS INFLUENCE ON RUNOFF-GENERATING PROCESSES

av

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M.Sc., Vrml

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Motto:

All STATISTICAL CALCULATIONS, no matter how sophisticated, performed on the rainfall data will REDUCE the amount of INFORMATION included in the original record.

A synthesis, which is a result of all statistical operations is merely a useful way to practical applications.



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PREFACE

Studies of the areal and dynamic properties of rainfall have been carried out in Lund since 1978. Most of the results were published previously. This work is a continuation of studies aiming at developing a basis for a better understanding of the rainfall-runoff processes. The results that have been presented entail vital practical implications with regard to the choice of rainfall input for modeling of runoff.

In the first part of this work (Chapters 1. and 2.), the background of the study and a summary of the results are given. The hypothesis which forms the framework of the investigations is presented; the general outlines of the research methodology which has been used are described; and the most important results and conclusions underlying the practical implications are stated.

The second part (Chapters 3. to 8.) consists of a number of original papers which - after being complemented and re-written - supply details concerning the performed studies. Some parts of original papers were removed in order to avoid repetitions. This part begins with an extensive literature overview giving the "state of the art report" on the field of rainfall analysis.

It is my hope that the results will improve our understanding of rainfall-runoff processes, and that they will be put to practical uses in attempts to make the modeling of runoff more exact.

A list of those publications which constituted the base for the present work is given below:

Falk, J, Jönsson, O, Niemczynowicz, J (1979), "Measurements of Rainfall Intensities in Lund". Department of Water Resources Engineering, Lund Institute of Technology/University of Lund, Report No 3023.

Niemczynowicz, J, Grahn, L, (1981), "Hydrological Instrumentation". Department of Water Resources Engineering, Lund Institute of Technology/University of Lund, Fifteenth Anniversary Report, No 3053.

Niemczynowicz, J, Jönsson, O, (1981), "Areal Variability of Rainfall Intensity". Department of Water Resources Engineering, Lund Institute of Technology/University of Lund, Fifteenth Anniversary Report, No 3053.

Niemczynowicz, J, Jönsson, O, (1981), "Extreme Rainfall Events in Lund 1979-1980". Nordic Hydrology, 12, 129-142.

Niemczynowicz, J, (1982), "Areal Intensity-Duration-Frequency Curves for Short-Term Rainfall Events in Lund". Nordic Hydrology, 4, 193-204.

Niemczynowicz, J, (1982), "Areal Intensity-Duration-Frequency Curves and Areal Reduction Factors for Short-Term Rainfall Events in Lund". Department of Water Resources Engineering, Lund Institute of Technology/University of Lund, Report No 3065.

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Niemczynowicz, J, (1984), "Properties of Rain" Chapter 3 for "Review of Rainfall Data Application for Design and Analysis". Specialised Seminar on Rainfall as the Basis for Urban Runoff Design and Analysis, Copenhagen, 24-26 August 1983, Water Sci. and Techn., Vol 14, No 8/9, 4-12.

Niemczynowicz, J, (1984), "Can the Rainfall Input be Modified so that Frequencies of Rainfall-Input and Runoff-Output will be Similar?". Written discussion, Specialised Seminar on Rainfall as the Basis for Urban Runoff Design and Analysis, Copenhagen, 24-26 August 1983, Water Sci. and Techn., Vol 14, No 8/9, 251-254.

Niemczynowicz, J, (1984), "Areal Rainfall - an Improved Input for Modeling of Runoff". Proceedings of Third International Conference on Urban Storm Drainage, Gothenburg, Sweden, June 1984, Vol 1, 335-344.

Niemczynowicz, J, Dahlblom, P, (1984), "Dynamic Properties of Rainfall in Lund". Nordic Hydrology, 15(1), 9-24.

Niemczynowicz, J, (1984), "Investigation of the Influence of Rainfall Movement on Runoff Hydrograph. Part I: Investigations on Conceptual Catchment, Part II: Investigations on Real Catchments in Lund". Nordic Hydrology, 16(2), 57-84.

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Rainfall studies presented in this report have been supervised by the Head of the Department of Water Resources Engineering, Professor Gunnar Lindh, to whom I am very grateful for convincing me that the results were worth presenting in this manner.

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1. BACKGROUND

1. BACKGROUND

In the last ten years, the use of mathematical modeling of rainfall-runoff processes has increased sharply. Considering the necessity of solving difficult water-management problems, especially in urban areas, the use of mathematical modeling is the only reasonable way to achieve an economical solution. When the benefits of using modeling in solving urban hydrological problems became recognized, the number of applications of runoff simulation models outside the universities began to increase. At present, many consulting firms and communities use runoff simulation models for the design and analysis of sewage networks. The urban runoff simulation models which are most frequently put to practical use in Sweden are: The Illinois Urban Drainage Area Simulator ILLUDAS (Terstriep and Stall 1974, Sjöberg et al 1981), and the Storm Water Management Model SWMM (Huber et al 1981). It is very important that experience in modeling, first gained in the universities, is transferred to a growing number of users. The question how to choose rainfall input is crucial where the accuracy of the results is concerned. No models can yield correct results if the input is wrong.

Mathematical runoff simulation models are, like all other models, a "simplified representation of a complex system", according to a definition given by Clarke (1972). In the case of runoff modeling, a catchment is a system described by a set of equations which form the model. The rain falling over the catchment, and the parameters describing the characteristics of the catchment, constitute the input to the system. The runoff flowing out from the catchment can be referred to as the output. Due to hydraulic interaction between the rainfall and the catchment, the shape of the rainfall hyetograph will be modified into a runoff-hydrograph shape. The input will be changed into output by the system. In order to describe the urban sewage system mathematically, state equations and output equations (or response functions) must be formulated. The state equation for most urban runoff simulation models is a continuity equation, the output equations

used in these models differ with regard to the degree of sophistication, ranging from a simple linear reservoir to fully dynamic wave equations. Both state and output equations require input if the rainfall-runoff processes are to be simulated. The input to the state equations - i.e., the input driving the system - is taken from meteorological data, usually rainfall or snowmelt. The input to the output equations usually consists of a set of parameters describing the physical properties of the catchment. If the model does not involve a stochastic component in the mathematical formulation, a model will be called deterministic, and the same input will always produce the same output.

Most of the existing rainfall-runoff models are deterministic. The set of parameters describing the catchment is usually adjusted to any particular catchment and even to any particular subcatchment. Rainfall data, however, are often scarce. The same existing data have to be used for many catchments. Moreover, the rainfall input usually consists of historical records or so-called design storms derived from one-point observations (see for example Keifer and Chu 1957, Sifalda 1973, Arnell 1981). In the simulation models, the rainfall input is usually assumed to be uniformly distributed over the catchment, regardless of the size of the catchment area. The input of uniform rainfall does not reflect real rainfall events, though. Nor does it take the areal and dynamic properties of real rainfalls, into account.

The hydrographs of runoff from the same rainfall event may be different on different catchments, even if the catchment parameters are the same. For example, the shape of the runoff hydrograph is influenced by the direction of storm movement in relation to the main direction of conduits. The shape of the runoff hydrograph also depends on the size of the catchment; the average areal rainfall intensity decreases when the area increases. If we use the same rainfall input for modeling the runoff from different catchments, an error in simulated runoff will be intro-

duced. Inaccuracy in runoff simulation obviously depends not only on the rainfall input, but also on the level of sophistication in the mathematical description of rainfall-runoff processes. The errors due to simplifications in rainfall description begin to play an important role only when other errors are of the same order of magnitude. Where the simple design of a new stormwater system is concerned, for instance a simple design storm and the rational method may still be adequate. For the analysis of complicated down-town sewer systems, though, the most sophisticated runoff simulation model may be needed. In this case, the relevant rainfall input must be chosen so that the temporal, areal and dynamic properties of the rainfall are taken into account.

The general hypothesis of the present study is that the rainfall input must be adapted to each particular catchment in order to avoid errors in the runoff simulation: the areal and dynamic properties of the rain must be taken into account. In order to reproduce real rainfall-runoff processes in a correct way, not even the use of highly sophisticated rainfall-runoff models is sufficient, if the rainfall input is based on one-point historical observations or design storms.

The main objective of this investigation is to identify those rainfall properties which have to be taken into consideration when choosing rainfall input for runoff modeling, and to quantify the errors which occur when traditional one-point rainfall-input values are used. This study has been limited to high-intensive storms, i.e. short-term rainfalls, used as input in runoff simulation models applied to the design and analysis of urban storm drainage systems.

2. SUMMARY

This chapter summarizes all the results, in details presented in Chapters 4. through 8. The hypothesis, which forms the framework of the investigations is presented, the general outlines, of the applied research methodology are described, and important conclusions stressing the practical implications are stated.

2. SUMMARY

2.1 Introduction

This work presents an analysis of the areal and dynamic properties of rainfall. It has to be stressed, however, that from a practical point of view, the main interest of hydrologists dealing with urban drainage systems is not the rainfall itself, but the runoff which follows the rain and causes several detrimental effects. In particular, we are interested in predicting how often certain characteristic runoff values - such as peak flow, volume, pollutant washoff etc. - will be exceeded. In other words, we want to know the return period for different characteristic runoff values. Of course, the easiest thing would be to perform the required statistical calculations on actual measured runoff values, but long and consistent runoff records are seldom available. Hence, we are forced to use rainfall as a predictor of runoff. In order to simulate runoff hydrographs, mathematical models are commonly used in transforming rainfall values into runoff hydrographs. The return period of simulated runoff occurrences is then assumed to be equal to the return period of the applied rainfall input. Measured rainfall series, however, do not necessarily reflect the true values of precipitation. Wind-field deformation, wetting and evaporation losses, instrumental errors, and human mistakes lead to that more or less incorrect values being subjected to analysis. The one-point rainfall data which are usually used, not necessarily reflect areal precipitation, which is a driving force for the runoff. In addition, the rainfall of a certain return period is not necessarily associated with the runoff of the same return period. This study attempts to identify the reasons for the discrepancy between rainfall and runoff frequencies, and to treat rainfall data in a manner that will allow us to use them for determining the runoff of a specified return period.

The most commonly used procedure is to process the rainfall series (usually one-point data) so that some kind of synthesis is obtained, such as intensity-duration-frequency (i-d-f)

relationships. Then, the different types of design storms with known return periods can be derived and used as an input for runoff modeling. Design storms are usually assumed to be uniformly distributed over a catchment, regardless of the size of the catchment or its geographical orientation.

Since i-d-f relationships comprise the statistical properties of a long time series of rainfall data in a comprehensive form, it is usually accepted that rainfall input derived from them possess a proper statistical justification. As long as the rational method was used, no proof could be found that statistical information taken from i-d-f curves was not always sufficient for the purpose of computing runoff in urban areas. When more sophisticated methods of runoff prediction came into common use, it was realized that design storms may not only give a false picture of a hyetograph, but also a false rainfall volume (Arnell 1982). Furthermore, it was soon realized that the rainfall frequency provided by i-d-f relationships does not correspond to the observed runoff frequency (Sieker 1978, Urbonas 1979, James 1981).

During recent years, a number of design storms with different shapes have been proposed (Amorocho 1981, Arnell 1982). With some of them, attempts have been made to reproduce the real shape of observed hyetographs. However, these design storms cannot reflect the dynamics of moving rainfalls, and they cannot represent the areal properties of the rainfall pattern. Many efforts have been made to overcome this discrepancy by changing the procedures utilized in deriving design storms, or by developing alternative types of design storms. One possible way seemed to be to use long rainfall series in continuous simulation of runoff, making statistical calculations on the output (Harremoes 1981, 1983). Another way is to utilize chosen historical rainfalls with calculated return periods as design storms for runoff simulation (Pilgrim and Cordery 1975). Yet another way was to use areal rainfall extrapolated from point measurements, or to apply areal reduction factors to point rainfall input (Bell 1976).

Most of these efforts to match the frequencies of predicted and observed runoff occurrences have not been very successful. All the methods have only focused on one cause for discrepancy at a time, while there are actually three main reasons why the return period of rainfall is not equal to the return period of runoff. The main hypothesis of this work is that the combined effect of areal rainfall, moving storms, and antecedent precipitation conditions has to be considered, if the frequencies of rainfall and runoff are to be matched. These three effects are summarized and discussed below.

1. Areal rainfall, which causes the resulting runoff, is never known exactly, i.e. the input from which the runoff is computed as output is uncertain. Since all rainfall measurements, apart from radar observations, supply point values while runoff is, by its nature, an areal process, assessments of areal rainfall values are necessary. Design storms, and even historical rainfalls used in runoff simulations, are almost always taken from one-point data.
2. Rainstorms move over a catchment. The speed and direction of the movement of a storm significantly affect the shape of the hydrograph. When a design storm is applied, the movement of a storm is not considered. The common rainfall-runoff models do not contain a routine for simulating moving rainstorms. Only a few researchers have attempted to include moving rainstorms in existing rainfall-runoff models (James and Scheckenberger 1982, Niemczynowicz 1984b, 1984c).
3. Antecedent precipitation conditions differ from storm to storm and influence the amount of runoff. (Urbonas 1979, Jacobsen and Harremoes 1981). Continuous simulation on historical rainfall series can account for this effect.

All those effects act simultaneously; and if we do not take them all into account when choosing rainfall input for

modeling runoff, errors in runoff prediction will be introduced. It is very probable that these errors are additive.

If the validity of the posed hypothesis could be proved, it would supply an indication as to why previous efforts did not succeed. It would also suggest what rainfall-pattern features should be included in rainfall input for runoff simulation.

The third effect that has been mentioned as causing discrepancy between rainfall and runoff frequencies, the antecedent precipitation conditions, does not involve the properties of rainfall and is therefore beyond the scope of this investigation.

The fact that areal measures of rainfall must be used for runoff prediction is generally recognized, but one-point rainfall data are still used in most practical applications. The reason is that the assessment of areal rainfall requires a dense network of gauges. Until some years ago, it was generally believed that areal rainfall statistics were not very different from one-point statistics where long time series were concerned. The question how different areal data are related to point data has not yet been answered in statistical terms. This work is an attempt to give such an answer.

The fact that the dynamic properties of rainfall are important for the runoff-generating process was not recognized until recently. Only few works have been devoted to the influence of rain movement on runoff hydrographs (Takahasi et al 1971, Surkan 1974, James 1981). As far as I am aware, no studies have been presented concerning the significance of rainfall movement for practical applications, such as the design of stormwater drainage systems. The questions whether and how the dynamic properties of rainfall must be considered when choosing rainfall input for runoff modeling can only be answered if the range of the effect is defined in statistical terms. This investigation aims to provide a necessary basis for answering these questions.

The studies reported in this work are based on measurements of short-term rainfall made on a network of raingauges situated in the city of Lund, Sweden. In the following section, the systems of data collection and data processing are described. Following that section, the studies concerning the areal and dynamic properties of rainfall are summarized.

2.2 Data Collection and Processing System

Twelve rain gauges have been installed to cover an area of 20 sq.kms.in the central part of Lund (Figure 2.1). Data from the gauges are transmitted via the telephone network to the receiving station at the laboratories of the Department of Water Resources Engineering.

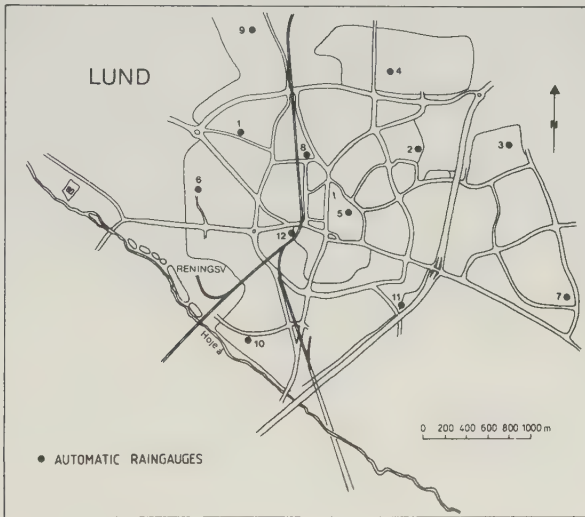


Figure 2.1 Location of the raingauges in Lund

In 1978, when the project started, there was no standard raingauge available that could meet the desired requirements of high accuracy as well as low price. Therefore, a gauge based on the tipping-bucket principle (see for example Ven te Chow 1964) was developed and manufactured. The volume resolution is, as an average, 0.035 mm per tipping, allowing intensities between 0.035 and 4.2 mm/min to be measured. The non-linearity in the relation between rain intensity and number of tipplings per time unit, expressed as an exponent,

varies from 1.02 to 1.05 for different gauges. A careful dynamic calibration of each individual raingauge was performed, and a special control routine to check the stability of calibration parameters in the field was developed (Falk et al 1979).

The data collection system is shown schematically in Figure 2.2. Each of the 12 raingauges is connected by a cable to a transmitter situated in the nearest house. The signal is transmitted on leased open telephone lines to the receiving station at the office. The signals are counted and the number of pulses during a preset time period is recorded on a tape puncher for all gauges.

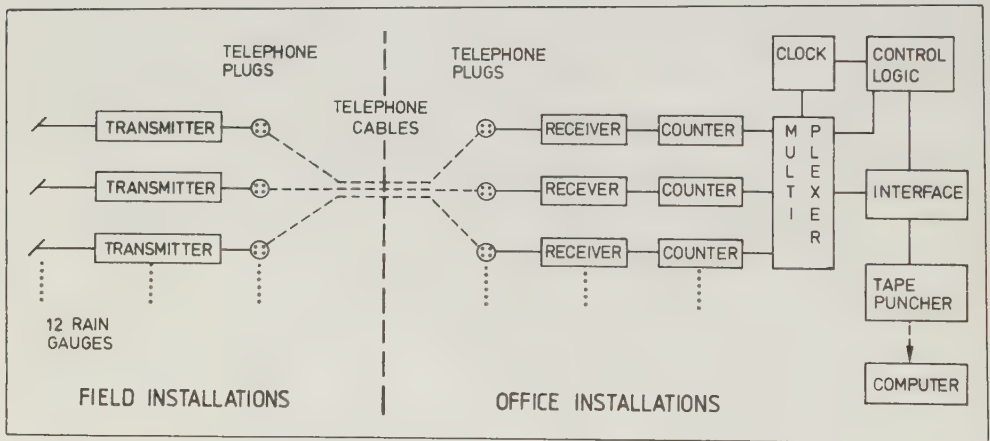


Figure 2.2 Data collection system for rainfall records

Recording of readings from all gauges takes place for each time period, during which at least one gauge has counted at least one pulse. For each recorded time period, a day number and a time from a digital clock is registered, assuring an absolute time synchronization between the gauges. The recording time interval is set to one minute.

The raingauge readings are stored as original, two-digit records representing the number of pulses per minute. A calculation of rainfall intensities is made as the last step of processing, usually on reduced data.

data by excluding all values below a preset threshold of rainfall intensity and duration.

Since our interest was mainly focused on high-intensity rainfall events, rain intensities below 2 mm/hour were excluded, which reduced the data by about 75%, but the total rain volume was only reduced by 5%. Due to malfunction of the gauges, there are gaps in the records. In order to be able to replace missing values, a routine for distinguishing them from zero values was developed. If one particular gauge showed zeros during "frontal rain", arbitrarily defined depending on a relation between rainfall intensity and duration, malfunction is assigned to this gauge, and a "minus sign" is written in place of the original data for this gauge.

If nothing but zero values has been observed for this gauge during "convective rain" between two "minus signs", malfunction of the gauge is assigned with regard to this rainfall, too. If more than 5 gauges are labelled as showing malfunction during the same event, the whole event is rejected. After this procedure, missing values are replaced by means of an interpolation procedure. A new file containing a complete field of data is created. Further statistical calculations can be performed either on the original data set or on a complemented data field.

A number of graphical programs can be applied to all files. An example of a three-dimensional plot of rainfall intensities taken from a data base is shown in Figure 2.4.

2.3. Extreme Rainfall Events in Lund 1979-1980

Ten extreme rainfall events observed in Lund during a period of two years, starting in June 1979 and ending in September 1980, were analysed with respect to point and areal intensities and dynamic properties.

An arbitrary criterion for the selection of extreme events was set at a maximum ten minutes intensity observed by any of 12 gauges.

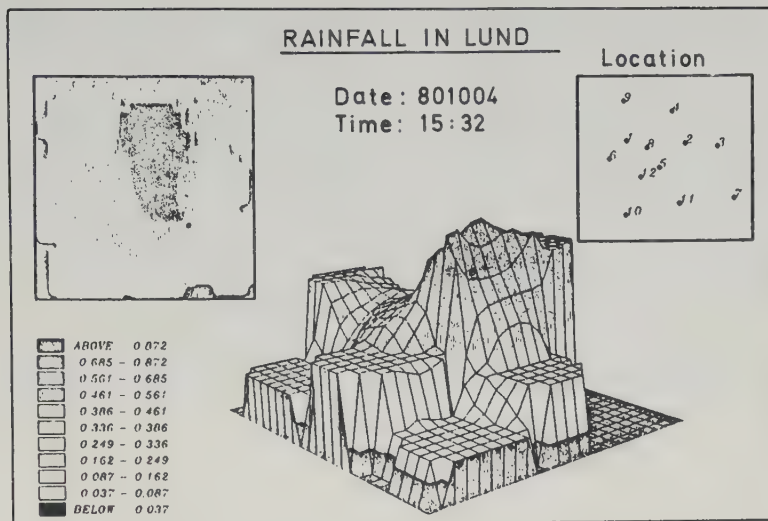


Figure 2.4 An example of graphical presentation of rainfall intensities in space by means of a color plot program

The maximum 1 minute intensity observed during the period of two years was 2.31 mm/min as a point value and 1.37 mm/min as an areal value for 10 sq kms. The maximum 10 minutes intensity was 1.07 mm/min as a point value and 0.94 mm/min as a 10 sq kms areal value. It was shown that all rainfall intensities decline with increasing duration and area.

Intensity-duration relationships for individual rainfall events were derived and compared with synthetic i-d-f relationships. It was shown that intensity-duration curves for individual events do not follow the synthetic curves smoothly with regard to any return period. The return period of one rainfall event can be different if different durations are considered. For example, the event presented as No 1 has a return period of about 7 years if maximum 10 minutes average value is concerned, but only 4 years return period if 30 minutes average intensity value is concerned. It is also shown that the volume of the rainfall definitely depends on the size of the area.

Data from observed extreme rainfall events were used as input to the Storm Water Management Model (SWMM) for simulating runoff from 20 sq.kms. catchment in the central part of the city of Lund. Changes in the storm drainage system in Lund were simulated and the results of these changes were evaluated. It was shown that when only one-point rainfall input was used, serious errors in the simulation of runoff were introduced. In an example taken from the simulated hydrographs, the error in simulated peak discharge was about 20% in relation to the observed value, even when one-point rainfall data were taken from the gauge situated in a center of the catchment.

An estimation of storm movement parameters was made by means of applying the spatial correlation analysis technique developed by Marshall (Marshall 1980). The procedure of estimating the velocity and direction of the drift is based on the sample cross-correlation between all pairwise combinations of gauges. Assuming spatial stationarity, the cross-correlation between two gauges is a function of the time-lag and the relative distance between gauges. The figure defined by the iso-correlation line moves across the network as the time-lag of the correlation increases. The velocity and direction of rain-cell movement were calculated as the velocity and direction of the centre of gravity of the area limited by the 0.7 correlation isoline. The diameter and the area of the figure limited by the 0.7 correlation line arbitrarily defined the size of the raincells.

The velocity of the raincells that was observed in connection with 10 extreme rainfall events in Lund varied between 7 and 25 m/s. The size of the raincells calculated for these events varied between 2.0 and 7.6 sq.kms.

Those meteorological situations which provoke the occurrence of extreme rainfall events in Lund were analysed on the basis of daily synoptic maps and wind data from the nearest airports. It was found that the most typical situation when convective storms are apt to occur in Lund is after the passage of a cold front, especially if the low pressure area is situa-

ted north of Lund and the air masses move from the south to the north.

2.4 Areal Intensity-Duration-Frequency Relationships

One possible way of explaining the statistical differences between point and areal rainfall is to derive areal intensity-duration-frequency relationships and compare them with traditional, one-point relationships.

Another way is to derive so-called statistical area reduction factors describing the relationship between point and areal rainfall depth with regard to different area sizes, different rainfall durations, and varying return periods.

Both areal i-d-f relationships and areal reduction factors were derived on the basis of rainfall records from twelve gauges covering an area of 25 sq.kms.in the city of Lund.

One-point i-d-f curves were developed by means of the usual ranking procedure performed on three years' data, recorded on each of 12 gauges. This resulted in 12 complete i-d-f relationships, each of them representing a point value. The mean point-value i-d-f curves were finally calculated by averaging the values from 12 relationships pertaining to all durations and return periods.

A three-year period of rainfall recording seems to be too short to justify statistical treatment. But following the so-called "station-years concept" (Baghirathan 1978), a three-year series recorded on 12 independent gauges can be approximatively equaled to $3 \times 12 = 36$ years of records from one gauge, if we use mean values to develop a regional one-point relationship. On the other hand, the main goal of this study was not to deliver a perfect one-point i-d-f relationship, but to compare one-point and areal rainfall statistics. Both point and areal relationships were developed from the same data base, and we believe that the results of such a comparison is fully reliable.

Areal i-d-f relationships were derived using the same ranking procedure on mean weighted values from combinations of the gauges. Each combination consists of 12 groups of gauges. In each combination, the same gauge is represented the same number of times. The point and areal mean values of the maximum intensity for different durations and return periods were fitted to a log-Pearson Type III distribution function.

The mean-value i-d-f curves for one gauge (point value) and 12 gauges (25 sq.kms.value) are presented in Figures 2.5 and 2.6.

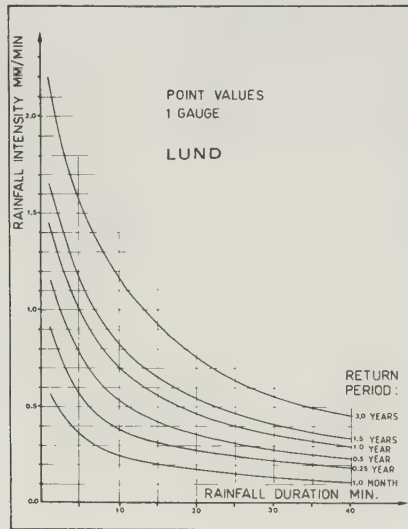


Figure 2.5 Point intensity-duration-frequency curves for the city of Lund

By means of rearranging the values from point and areal i-d-f relationships, the statistical areal reduction factors, pertaining to different durations and return periods were developed. The factors for a 1-year return period are shown in Figure 2.7, with rainfall duration as a curve parameter. Figure 2.8 shows the area reduction factors for 10 minutes' rainfall duration with the return period as a curve parameter.

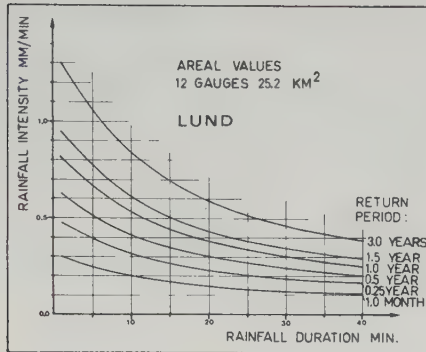


Figure 2.6 Areal intensity-duration-frequency curves for the city of Lund. Area 25 sq kms

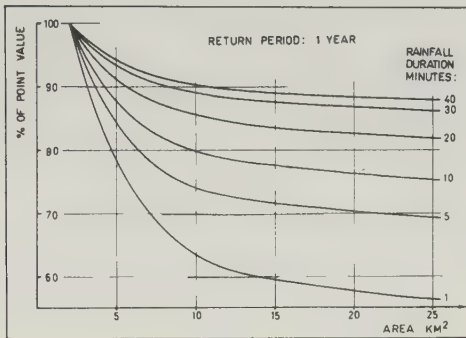


Figure 2.7 Statistical areal reduction factors. Return period 1 year

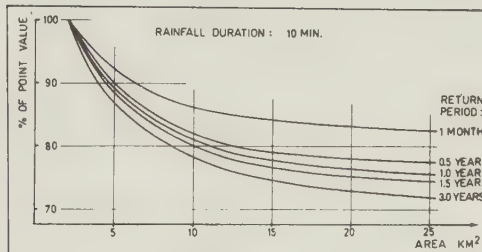


Figure 2.8 Statistical areal reduction factors. Rainfall duration 10 minutes

The most important conclusions can be summarized as follows:

1. The magnitude of the difference between point and areal rainfall values depends on duration, on the return period, and on the size of the area.
2. The most significant differences between point and areal rainfall values can be found where short durations and long return periods are involved.

From the presented point and areal i-d-f curves, it can be noticed that the return period of a given rainfall intensity as a one-point value has to be increased by about 50% for a catchment size of 25 sq.kms. and for durations up to 30 min.

A detailed description of the data base that has been used, and of the procedure employed in deriving areal i-d-f relationships, has been submitted previously (Niemczynowicz 1982).

By using areal i-d-f relationships when deriving design storms, the rainfall input for runoff modeling will be improved. However, the approach is in fact more practical than complete, as areal i-d-f relationships do not describe the dynamics of the moving storms; nor do they reflect changing moisture conditions.

2.5 Statistics of Rainfall Movement Parameters for the City of Lund

It is generally recognized that the shape of the runoff hydrograph and the peak flow discharge depend not only on the catchment characteristics and the time distribution of the rainfall pattern, but also on the dynamic properties of the rainfall, such as the velocity and direction of raincell movement in relation to the direction of the main watercourse in the catchment. This statement implies that rainfall dynamics should be considered when choosing an adequate rainfall input for the modeling of runoff. The possible range of the impact of rainfall movement on runoff-generating

processes can only be judged if the rainfall velocity and direction are known in statistical terms. The probability distribution of rainfall directions for the city of Lund was derived on the basis of about 400 rainfall events observed during a three-year period.

A simple program for the determination of the velocity and direction of storm movement has been developed. The algorithm for the determination of the velocity vector is a modification of a well-known three-point method (see Hindi and Kelway 1977). The method is based on a triangulation on time to the peak value of rainfall intensity observed in three gauges. The method requires that some easily recognizable characteristic mark is present in a rainfall pattern. In our case, the maximum intensity during one minute, observed at different gauges, was used as the characteristic feature. Having learnt the time when this peak occurs in each gauge, we can calculate the average velocity vector for each triad of gauges. The final velocity vector is calculated as an arithmetic average of all combinations of gauge triads. The final direction is calculated as a sum of normalized velocity vectors.

The performance of the program was checked by means of a comparison of the results with previously calculated storm velocities and directions for extreme rainfall events in Lund (Niemczynowicz and Jönsson 1981), applying Marshal's method (Marshal 1980); see also section 2.3. Good agreement between the two methods was achieved. Further confirmation of the reliability of the results was obtained by correlating the calculated storm velocities and directions against observed wind velocities and directions.

Storm velocity and direction were calculated for 400 rainfall events observed in Lund during the three-year period. Statistical analysis of the results yielded the distribution and probability of rainfall velocity (Figure 2.9) and the relative frequency of storm movement direction (Figure 2.10).

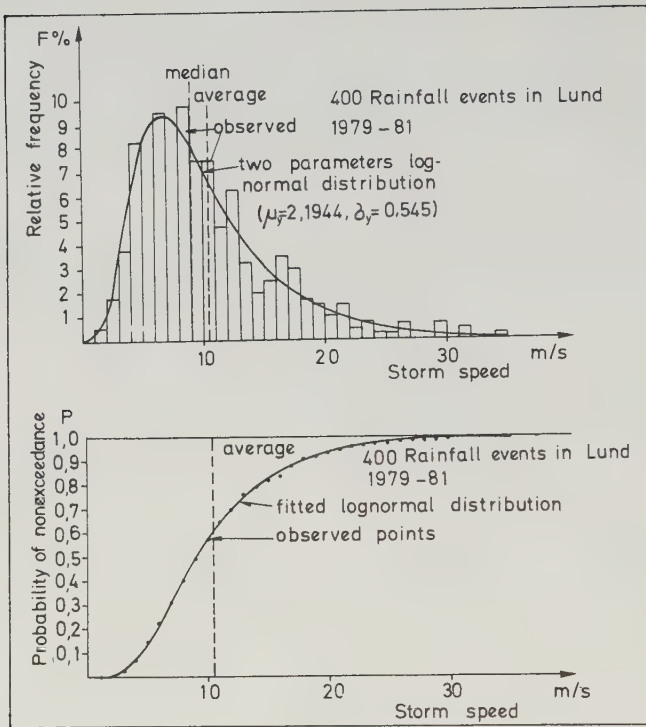


Figure 2.9 Relative frequency of storm velocity in Lund and probability that the storm velocity will not exceed values given by abscissa

A clear picture of the seasonal variation with regard to storm velocity and direction emerged. Two main directions of rainfall movement are visible: the first, prevalent for most of the year except during summer, is from the west and north-west. Rainfalls moving in this direction mainly possess average or low intensity and high velocity. The other chief direction is from the south and south-south-west. Storms moving in this direction mainly occur during the summer and are characterized by high intensity and low velocity.

Figure 2.11 shows the relative joint frequency of storm movement velocity and direction.

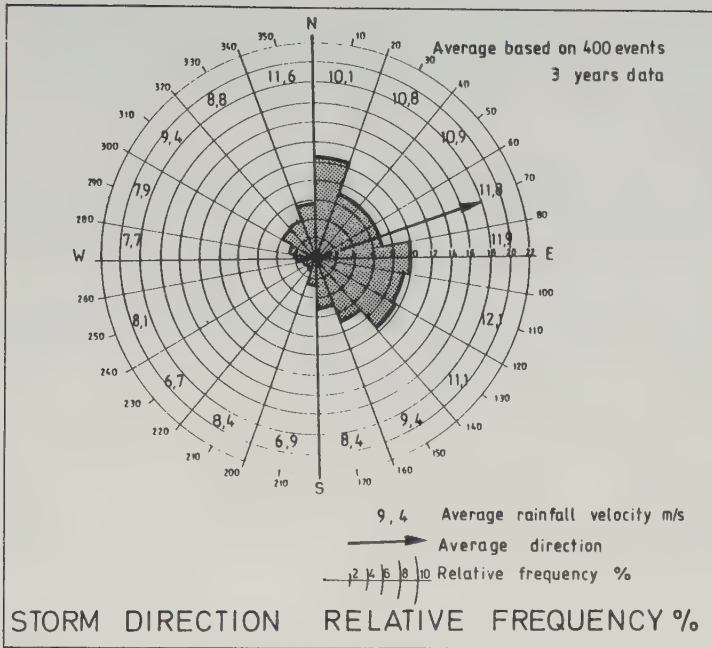


Figure 2.10 Relative frequency of storm movement direction in the city of Lund

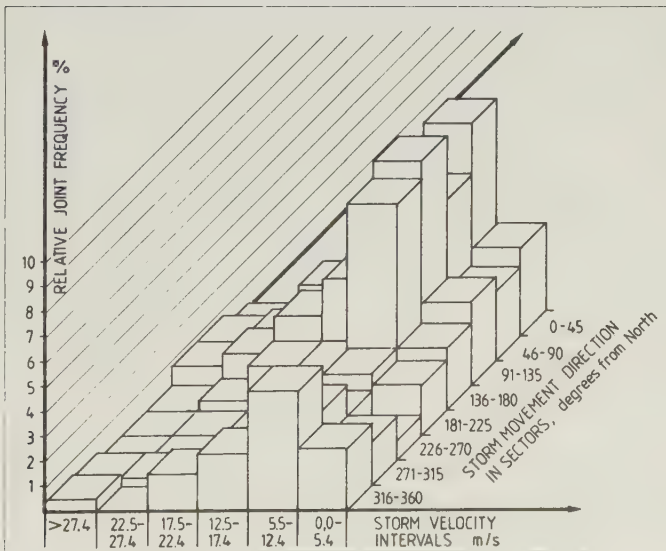


Figure 2.11 Relative joint frequency of storm velocity and direction in the city of Lund

A good correlation between storm movement parameters and wind movement on 600 and 700 mb indirectly confirms the reliability of storm movement parameters calculated from the point data.

Perhaps the most important result of this study is the confirmation of the fact that information about rainfall movement is actually present in a set of data from a network of point measurements. If the network is sufficiently dense and the time resolution of registration sufficiently good, the rainfall movement parameters can be extracted from the data by means of a simple procedure.

Wind velocity at 700 mb is a very good indicator for storm movement. Most airports measure wind at this level. Airport wind data can be used in rough estimations of storm movement parameters.

The results obtained in this way have clear practical implications. An analysis of storm velocities indicates that rainfall events with high intensities, knowledge of which is essential where design purposes or consequence analysis is concerned, may have lower-than-average velocities. On the average, though, these velocities are much higher than those velocities of water flow that usually occur in sewers. Thus, the "worst" situation, when the storm velocity equals the velocity of the flow, has a low probability of occurrence. The relative frequencies of storm movement direction that are reported in the paper can be used to judge the probability of "worst" events, when the main direction of sewers in the catchment coincides with the most probable direction of the storm movement. These "worst" events can be expected to occur only in those catchments in Lund which have a general orientation of sewers in the north-north-east direction.

A detailed description of this study has been presented elsewhere (Niemczynowicz and Dahlblom 1984).

2.6 Influence of Rainfall Movement on Runoff Hydrograph

The influence of rainfall movement on runoff hydrographs was studied, using rainfall data from Lund and the Storm Water Management Model for runoff simulation on different catchments in Lund. Here, for convenience, the effect of rainfall movement on peak flow discharge is referred to as the "maximal directional bias" and defined in the following terms:

$$\text{MAX DIRECTIONAL BIAS} = \frac{\text{QDOWN} - \text{QUP}}{\text{QUP}} \quad 100\%$$

where

QDOWN = peak flow generated by storms moving downstream

QUP = peak flow generated by storms moving upstream

At first, the influence of rainfall characteristics and of catchment parameters on the directional bias value was tested by running the SWMM with simulated storm movement on a conceptual catchment, using rainfalls with constant intensity during their duration (block rainfalls). The conceptual catchment consisted of 12 subcatchments with a total area of 50 ha each, connected to one another by 12 identical straight conduits. The time step of runoff simulation was established at 1 minute. The general shape of the relationship between storm duration and intensity versus directional bias values was investigated with regard to different storm velocities. Figure 2.12 shows the relation between storm duration and directional bias values with different storm intensities, and in cases where storm velocity equals average flow velocity.

The relationship was then tested on several real catchments in Lund; so-called design storms and real, observed rainfall events were used in the process. Figure 2.13 shows this relationship derived for one real catchment in the city of Lund, using block rainfalls as input. Figure 2.14 demonstrates some examples of runoff hydrographs simulated on different catchments in Lund; here, observed rainfall events and simulated downstream and upstream storm movement, were employed.

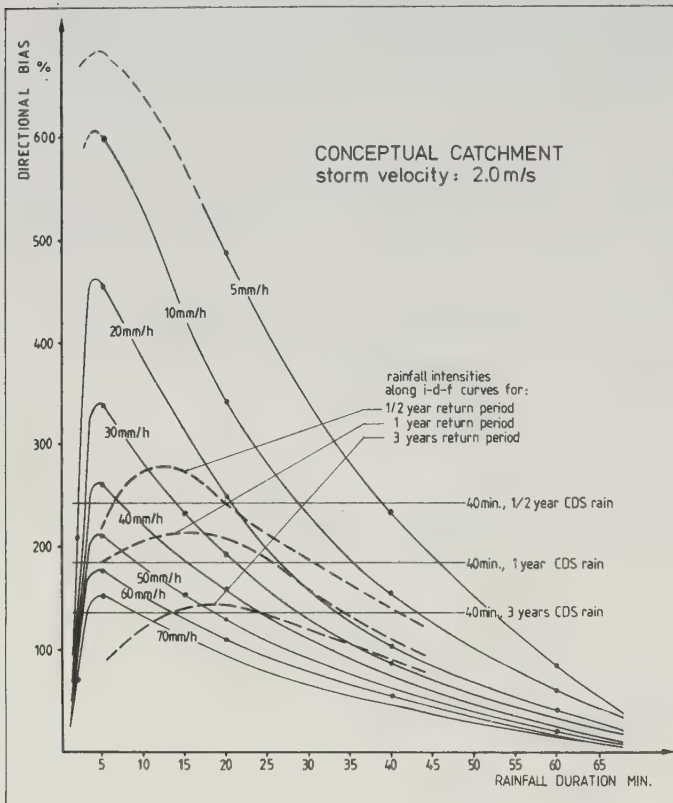


Figure 2.12 Relationship between storm duration and directional bias. Conceptual catchment.

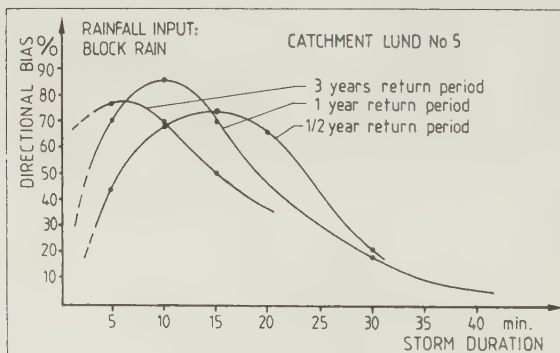


Figure 2.13 Relationship between storm duration and directional bias. Lund catchment

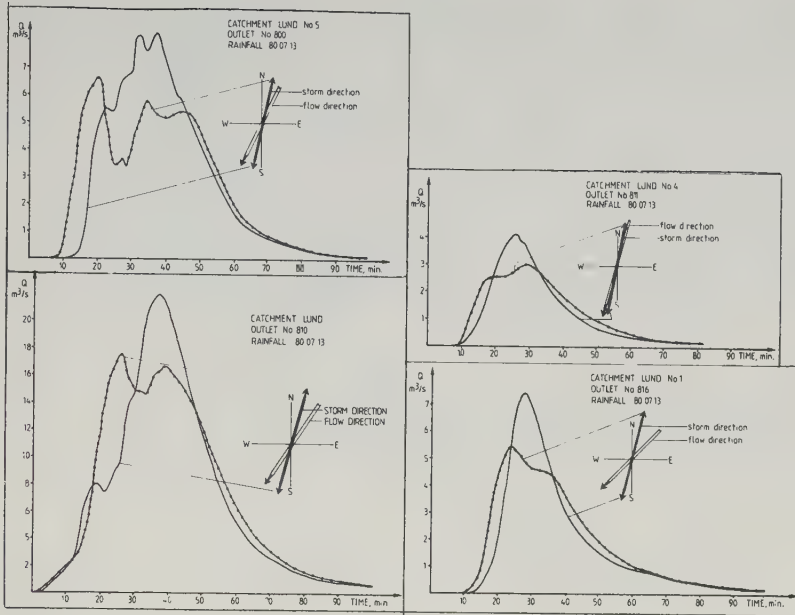


Figure 2.14 Examples of runoff hydrographs for downstream and upstream storm movement

The most important conclusions can be summarized as follows:

- Maximal directional bias can be expected in the case of storms moving downstream with a velocity equal to the average flow velocity in the sewer network.
- Maximal directional bias can reach values of several hundred percent, but this only occurs in respect to storms with short durations which generate low peak flows, and on catchments with an unrealistic sewer network.
- The maximal directional bias which was shown to apply to real catchments is smaller than that for the conceptual catchment, but it can still reach significant values up to about 80%. In other words, the peak discharge from a storm moving downstream may be about 80% higher than that which derives from a storm moving upstream, or about 30% higher than the peak discharge pertaining to a stationary storm.

- Long catchments with straight conduits running more or less parallel to the long axis of the catchment show a higher directional bias than catchments with more complicated sewer geometry.
- If the rainfall input follows the i-d-f relationships, maximal directional bias will occur at durations which approximately equal $1/5$ to $1/3$ of the concentration time for the catchment.

2.7 Probability of the Occurrence of Directional Bias

Once we know the statistical characteristics of storm movement and the magnitude of the greatest possible directional bias, an attempt can be made to calculate the probability that certain directional bias values will occur in differently oriented catchments. Maximal bias will only occur if a rainfall of a certain duration and intensity moves with a certain velocity exactly parallel to the direction of the conduits. There is a certain, in this case known, probability that storms move with this velocity and direction. The probability that the directional bias will exceed certain values was calculated in respect to differently oriented catchments in Lund (Figure 2.15).

A detailed description of this study has been provided elsewhere (Niemczynowicz 1984 b,c).

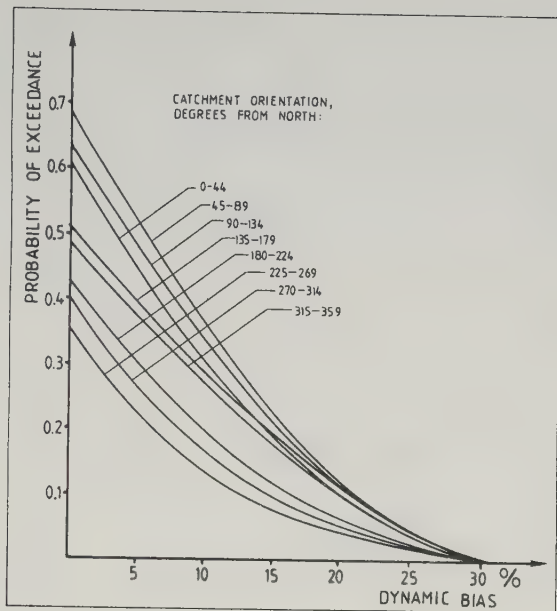


Figure 2.15 Probability that peakflow generated by storms moving downstream will exceed peakflow generated by stationary storms with percentage value given by abscissa

2.8 Conclusions

On the basis of rainfall data collected from 12 gauges distributed throughout the city of Lund, it was shown that both the areal and dynamic properties of rainfall influence the shape of the runoff hydrograph and the peak flow discharge. The areal rainfall is statistically different from point rainfall. The probability that a certain rainfall intensity will occur as an areal value is lower than the probability that the same intensity will occur as a point value. Information about storm velocity and direction exists in point rainfall data from a dense network of gauges.

Rainfall movement characteristics can be used in order to determine which catchments are most exposed to the effect of directional bias. Catchments oriented along the most frequent storm movement direction can expect higher peak flow discharges in comparison with catchments oriented in

other directions. Rainfalls with movement parameters yielding the maximal values of directional bias have a low probability of occurrence. Therefore, the error in simulating peak discharges using stationary storms as an input is not very important from a purely practical point of view, though it is certainly of significance in engineering contexts.

3. PROPERTIES OF THE RAIN, "STATE OF THE ART"

This chapter presents literature studies performed by the author. The general outlines of the traditional and recent methodology used in point and areal rainfall analysis and statistics, are described.

This chapter is, to a major extent, based on "Review of Rainfall Data Application for Design and Analysis", section "Properties of Rain", written by the author and presented on IAHR Specialized Seminar on Rainfall as the Basis for Design and Urban Runoff Analysis, Copenhagen, Denmark, 24-26 August 1983.

3. PROPERTIES OF RAIN, "STATE OF THE ART"

3.1 Point Rainfall Statistics

3.1.1 General

The interest in rainfall phenomena is as old as the human civilization, water being a crucial factor in human welfare. The oldest systematic notations about rainfall can be found in a meteorological register kept by Claudius Ptolemeus at Alexandria in the first century A.D. But there are only a few places in the world where a continuous series of rainfall records, kept for as long as 200 years, can be found. Rainfall records with good registration accuracy, providing figures which are relevant to requirements of modern applications - for instance, the designing of storm water systems in cities, - seldom extend for longer periods than 60-70 years.

Due to variability in time, the rainfall records usually consist of a great amount of data which in most cases represent volumes observed during some period of time (years, seconds). It is not convenient to use all these data in order to characterize rainfall conditions. For example, we cannot answer the question about rainfall conditions by repeating a 40-year rainfall series of daily measurements. Such an answer includes all the information available, but is still unpractical. Some kind of synthesis is necessary. We can, for example, state the average yearly precipitation. Answering in such a way, we reduce the amount of information and omit important features: but we gain immediate understanding as well as the opportunity of making comparisons.

All statistical calculations performed on rainfall data, no matter how sophisticated, will reduce the amount of information included in the original record. A synthesis, which is a result of all statistical operations, is nothing but a useful way to practical applications.

When dealing with rainfall data, we always talk about average values of rainfall depth or rainfall intensity. In order to recognize fine structures of temporal variability, we must

use a fine time resolution in the rainfall measurements. Apart from radar measurements, the finest time resolution of rainfall measurements reported in the scientific literature was applied by Semplak and Keller (Semplak and Keller 1969). It was concluded that "one scan per second is needed to resolve some of the intensive showers". Obviously, it can be said that even a one-second value is an average value and that if a finer time resolution were used, even subtler variations in the rainfall intensity would be found.

3.1.2 Definitions

The simplest way of making statistical calculations on rainfall data in order to achieve a synthesis consists in calculating simple arithmetic averages of rainfall volume or rainfall intensity. Averaging can extend over longer periods like years, months, and days, including rainfall events and dry periods, or over shorter periods such as minutes or hours, including rainfall events only. Averaging during rainfall events can be performed during equal time periods, starting at the beginning of the rainfall; the result will be called "average rainfall intensity (or depth) over a given time period". Averaging can also be carried out over different time periods (durations), time periods being chosen so that the average rainfall intensity for each duration will be maximal for this event. In this case the result will be called "maximum average rainfall intensity". The rainfall with constant rainfall intensity throughout its duration has a rectangular shape on the intensity-time plane; therefore such a rainfall is called a "block rainfall".

Maximum average values of rainfall intensity over different time periods are shown in Figure 3.1.

As can be seen from Figure 3.1 the longer the period of averaging, the greater the difference between the average maximum value and the real maximum of rainfall intensity. If

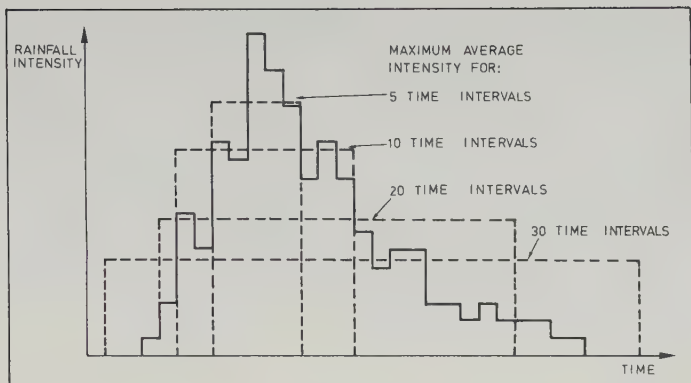


Figure 3.1 Definition of maximum average rainfall intensity for a given duration

the averaging is carried out during a longer period than the actual duration of the rainfall event, the average rainfall intensity is calculated as the total rainfall volume divided by the duration. In this case, the relation between rainfall volume and duration can be far from what is really observed. The actual rainfall volumes for these durations might be quite different from that obtained by means of a simple averaging procedure.

The other characteristics of the point-rainfall pattern are usually defined according to Figure 3.2. (Gottschalk and de Maré 1976, Eli and Croley 1977).

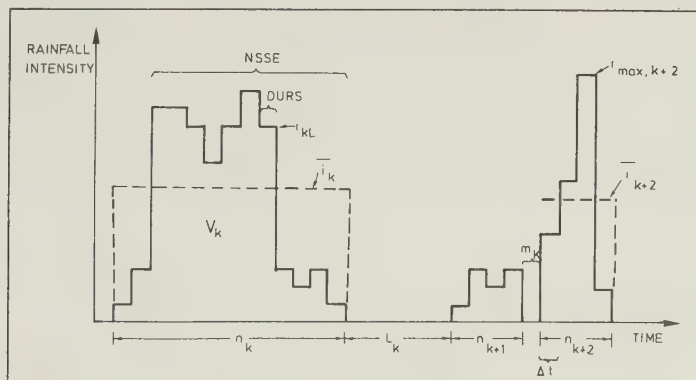


Figure 3.2 Definition of rainfall pattern

n_k	- duration of k rainfall event, or so called "Wet Spell"
l_k	- duration of dry period between events or "Dry Spell", or "Inter-Arrival Time" between rainfall events
m_k	- duration of time period between storm segments, or "Inter Arrival Time" between storm segments
i_{kL}	- rainfall intensity during time interval L
$\bar{i}_k$	- average rainfall intensity during event k and duration n
$i_{\max}$	- maximum rainfall intensity during event k+2
v_k	- rainfall volume per event k
Δt	- chosen time interval
NSSE	- number of storm segments in a rainfall event
DURS	- duration of each storm segment

3.1.3 Assumptions, Testing and Correction of Rainfall Data

Before measured rainfall data can be used in any statistical treatment, the data must be analysed in respect to their quality, i.e. accuracy of registration, possible error sources, internal and external changes which might have occurred, representativity. All statistical calculations made on precipitation data are based on some assumptions about the quality of the data and the nature of the precipitation phenomenon. The validity of those assumptions can be tested with the aid of known statistical tests. A list and a short description of the most important assumptions applied in statistical analysis of rainfall data are provided below. (Partly indebted to Sevruk and Geiger 1980). Given references denote recent applications of described methods.

1. Measurements reflect the TRUE VALUES of precipitation.
This assumption is practically never valid. Wind-field deformation, wetting and evaporation losses, instrument errors and human mistakes lead to more or less incorrect values being subjected to analysis. Measures which can

improve data include control of raw data, and correction. (Allerup and Madsen 1979, Sevruk and Geiger 1980, Sharon 1980).

2. Data are CONSISTENT. All data come from the same population. No internal changes occurred in the measurement system during the observation period. Double Mass Analysis is commonly applied to check this assumption. (f.ex. Bouvette et al 1982).
3. Data are HOMOGENEOUS. No changes occurred during the observation period in the external conditions affecting the measurements. During long periods of measurements, the external conditions in the vicinity of the gauge often change due to, for example, urbanization, growing trees, etc. Checking-Double Mass Analysis.
4. A data series is STATIONARY. Non-stationary effects can be caused by hydroclimatological changes, trends, periodicities, human activities, etc., the result being that the mean value, the standard deviation, and the moments of higher orders change with time. This assumption surely does not apply to partial duration series. The significance of non-stationarity can be tested by means of general tests such as Student's test, the F-test, the Rank dispersion test, the Run test, etc. (Bobee and Robitaille 1977, Eggers 1975).
5. Data are INDEPENDENT. No correlation exists between precipitation units. This assumption cannot be applied to partial duration series of short-term rainfall, where consecutive segments of rainfall events are highly correlated. Available tests are, for instance, the rank-correlation test, counting ranks, the CV-test etc. (Bobee and Robitaille 1977, Restrepo-Pasada and Eagleson 1982).
6. A data series is of SUFFICIENT LENGTH. The errors are a function of the length of the record. With more than one station, the data length can be expanded by means of

regional studies (station-years concept). (Dickinson 1977, Baghirathan and Shaw 1978).

7. Extremes of precipitation follow a specified DISTRIBUTION. Test methods: plotting positions based on different formulas (Cunnane 1978, Srikanthan and McMahon 1981), Chi-square test, Kolmogorov-Smirnov test, Sign test, Otten and Van Monford test (Otten and Van Monford 1978), δ_1/δ_2 ratio test (Dickinson 1977), test for distinguishing between Pearson types, comparison between estimates and observed data (Bobee and Robitaille 1977). Estimated PARAMETERS describe the assumed distribution. Different procedures for parameter estimation produce different parameter values. Different criteria are used in parameter estimation: the method of moments, the least square method, the maximum likelihood method and others. (Otten and Van Monford 1980, Houghton 1978).

3.1.4 Statistical Calculations on Point Rainfall Data

For hydrologists, one vital reason for analyzing rainfall data is a desire to be able to calculate or to predict the results of rainfall that are visible on the ground: i.e. the runoff. Thus, practical applications of rainfall data always involve using rainfall for predicting runoff occurrences or other phenomena following the runoff. For example, frequency analysis of rainfall volumes is used for predicting runoff volumes or peak discharges. Predicted runoff characteristics are, in turn, used in the designing of storm water systems, in analyses of complicated sewage networks, in calculations of pollution washoff, in the designing of retention basins, etc.

In Figure 3.3, an attempt is made to systemize possible ways of analyzing point-rainfall data. The choice of analysis obviously depends on the final application.

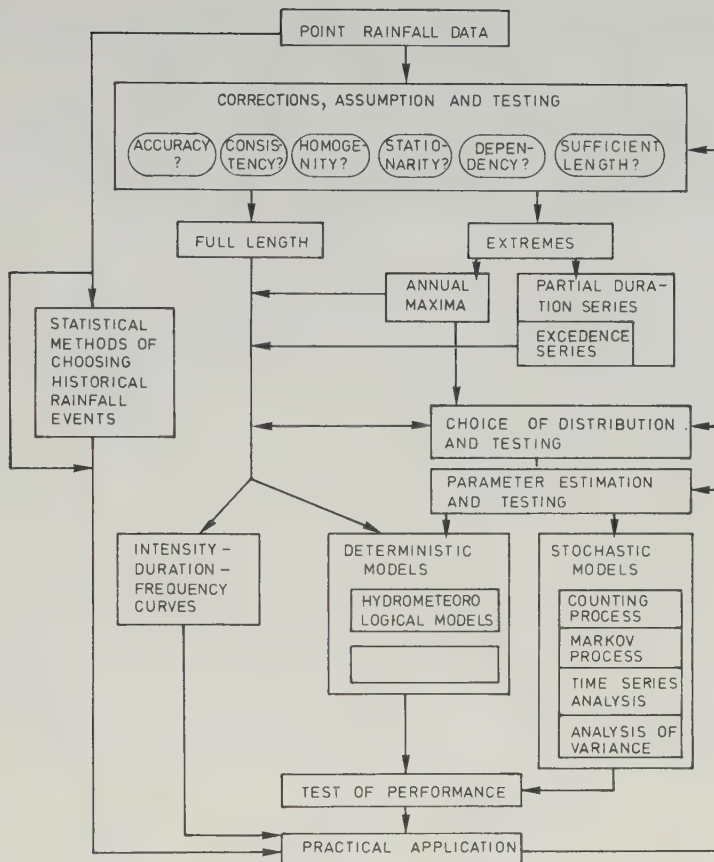


Figure 3.3 Point-rainfall data analysis

In some applications, it is possible to use the measured rainfall values directly. For example, an observed single rainfall event, during which the runoff or pollution load has been observed, can be used as an input when calibrating a runoff simulation model. In respect to other applications, it is enough to use a simple block rain, i.e. the average value of rainfall intensity over a given period. Most practical applications require that the rainfall input has a

known return period. The statistical meaning of the term "return period" implies that some statistical operations must be performed on the rainfall data series. Return periods applicable to urban hydrological problems are often comparable to the length of the available series of measurements, and so-called design storms can be derived from this series.

The relations between the intensity or depth, the duration, and the frequency of rainfall play a particularly important role in the solution of many engineering problems (Meinzer 1942, Chow 1964). These relations are usually derived from one-point data; they are called depth-duration-frequency (d-d-f) curves or intensity-duration-frequency (i-d-f) curves. In order to develop i-d-f relationships, the frequency analysis of maximum average rainfall intensity is made for various durations of rainfall. Different frequency distribution functions may be fitted to observation points in order to smooth out the curves on the intensity-frequency diagram (Viessman et al 1972, Sevruk and Geiger 1980). It should be emphasized that the i-d-f curves link occurrences that do not necessarily belong to the same storm; thus they only represent the average intensity expected for a given duration. From i-d-f relationships, so-called design storms can be derived. A block rain with constant intensity over its duration is an example of an extremely simple design storm which can be derived directly from i-d-f curves. Other examples of typical design storms are: Chicago Design Storm (Keifer and Chu 1957), Sifalda Design Storm (Sifalda 1973), Triangular Design Storm (Yen and Chow 1980). Different types of design storms, types which have recently gained recognition, can be derived directly from the measured time series of rainfall by means of analyzing simulated runoff series. Rainfall events which correspond to the design frequency are chosen for further simulations (Johansen and Harremoës 1975, 1979). In other applications, long historical rainfall records can be used.

An original method of deriving the statistical parameters of runoff, called "staged approach", has recently been developed in Denmark (Harremoës et al 1983). The complete available series of rainfall record is used as an input to a runoff-simulating model, and the calculations of the return period are carried out on the basis of the simulated runoff series.

Another way to produce a rainfall-pattern synthesis consists in the mathematical simulation of rainfall series. Two different approaches are available, either a deterministic or a stochastic procedure. A deterministic approach would use hydrometeorological information about atmospherical conditions and known physical laws in order to model situations when rainfall can occur. This approach includes, for example, the three-dimensional numerical model of an isolated thunderstorm developed by Shlesinger (Shlesinger 1978, 1980). Another example is a hydrostatical model for the numerical simulation of tropical cyclone development with latent heat release developed by Rosenthal (Rosenthal 1978). Such models contribute to the basic understanding of rainfall-generating processes, but can hardly find application in practical urban hydrology problems because they require too many usually unknown data.

There are also applications when interest of hydrologists extends beyond the length of the available historical record of the rainfall. Only probabilistic models, applied to existing series of measurements, can provide such an extension. The statistical properties of the observed rainfall can be used in the generation of future events. Mathematical models which can produce rainfall series are called stochastic models. The performance of a stochastic model is judged to be satisfactory if the model parameters preserve as much of the rainfall characteristics as possible. Stochastic models can be subdivided into: (Chow 1964, Raudkivi and Lawgun 1974).

1. The counting process which is, in principle, a sampling of simple events of a specific type. Such models assume

that the rainfall series consist of internally independent, purely random stochastic values. Both assumptions are rarely valid in natural conditions.

2. The Markov chain model, which allows for sequential dependence of data by means of so-called transition probabilities, i.e. the probability of a number of rain units following each other per given period of time. If we assume that the particular rainfall unit only depends on a previous unit, we have a first-order model. Dependence on more than one previous unit implies the use of the second, third, etc. order of model. Complexity and difficulties in establishing a transition probability matrix for higher model orders are limiting factors where applications are concerned.
3. The time series models, which involve a reconstruction of the basic structures of the observation series as trends, periodicities and persistence. In general, the time series is composed of two elements, a deterministic element involving trend and persistence and a stochastic element. Trends are normally described with the aid of linear functions or polynomials. Periodicity can be detected by correlograms or spectral analysis. The stochastic element may be an independent random variable generated, for example, by the Monte Carlo method, or it may show persistence (Box and Jenkins 1970, Yevjevich 1972, Raudkivi and Lawgun 1974).

3.1.5 Stochastic Models

Since the early 1960's, a number of models have been constructed for the simulation of precipitation sequences at one fixed point. Most of the early models were based on the assumption that precipitation is the result of a stochastic process, and simple Markov chains can be used for simulating wet and dry sequences. Synthetic rainfall data, produced by the models, can be used as input for modeling hydrological systems in order to obtain a better understanding of the per-

formance of the system, and to predict the system response from rainfall events with known return periods.

One of the best-known models was developed by Amorocho and Wu (Amorocho and Slack 1970, Wu 1973). The process of event sequence simulation consists in generating storm-band series by means of the Monte Carlo method. When determining the frequency distributions or variables, care was taken to consider seasonal trends and possible correlation between variables. The parameter estimation of the distribution was made either by means of the method of moments, or with the aid of the maximum likelihood method. The goodness of fit was tested by the chi-square and the Kolmogorow-Smirnof tests. The following distribution functions were found to fit the variables: beginning date of season - truncated normal, time between storms, storms bands and band duration - Weibull, number of bands within a storm - negative binomial, total precipitation depth in a band - regression on band duration (Amorocho and Wu 1977). Amorocho's model was then expanded to allow for the simulation of precipitation fields. (See also section 3.2.5).

Raudkivi and Lawgun (Raudkivi and Lawgun 1974) have developed another stochastic model for the generation of rainfall sequences, based on 10-minute time units. It includes the use of dependent time series and a random component that is non-normally distributed. The generated records for three climatically different regions have shown that the statistical characteristics of the historical records are preserved, and good-quality data are produced.

Bruin has investigated the influence of persistence on the length of dry and wet spells. In the proposed model, the number of parameters is reduced to two by the use of an empirical correlation function. The first parameter describes the overall probability that a day is wet or dry; the second parameter accounts for persistence (Bruin 1980).

Buishand has studied how the simplification of the general assumptions in the modeling process influence the goodness of fit. It was concluded that some features of the rainfall are hardly sensitive to the choice of modeling process, cumulative frequencies of 30-day totals can equally well be predicted by the models with serial correlation between rainfall amounts within a wet spell as by the models without serial correlation. Similarly, it is not necessary to use more advanced models for monthly extreme values. (Buishand 1978).

Eli and Croley have developed a stochastic model for simulation of the time of occurrence of non-stationary hourly precipitation. The problem of modeling the persistence of wet and dry periods was avoided through alternate modeling procedures. The Poisson process was utilized in order to schedule the first storm segment, corresponding to the beginning of a storm event. The dry periods separating storm events, according to the Poissonian assumption, represent an independent random variable. The random variables describing the inter-arrival times between events are exponentially distributed. On the same assumption, the inter-arrival times between the storm segments, the number of storm segments, and the duration of each storm segment were defined as random variables whose values are positive integers. Smoothed-out empirical frequency distribution functions were adapted to those variables. The nonstationarity of variables was represented by the estimation of various properties pertaining to six different periods within the year. This model of a storm occurrence, entirely described by independent random variables, is much easier to construct than other persistence models. (Eli and Croley 1978).

A different model for simulating the probable temporal distribution of rainfall, based on the analysis of variance, was developed by Sieker. The statistical procedure called analysis of variance has mainly been used for testing the significance of the effects of the defined components against the effects of the random component in a hydrological process.

Sieker uses a set of simulation equations derived from two-fold analysis of variance for generating the rainfall data. The equation employed in the simulation of the temporal distribution of rainfall contains three terms: the first term represents the average of temporal distribution of all rainfall events of the sample; the second term is a decision quantity of the model for determining the recurrence interval and is constant for all the time intervals of one event. The third term is a random term and represents the variation between the time distribution of all rainfalls and the average time distribution. The integral of the simulated events does not agree with the average sum of all events of the given duration and frequency. A correction factor was used in order to rectify this effect. A similar model was then developed on the basis of threefold analysis of variance; it was used for simulating the probable spatial distribution of rainfall events. (Abraham et al 1976, Sieker 1975, 1977, 1980, Sieker et al 1976).

3.1.6 Extremes of Precipitation

From a practical point of view, the extreme values of precipitation are of the greatest interest. Damages to the constructions in a watercourse, flooding and pollution in the case of underdesign, or economical losses in the case of overdesign will be the price to pay for mistakes made in predicting the extremes of precipitation. On the other hand, prediction of the extremes of precipitation is a most difficult task to do well, since the confidence limits expand rapidly with the return period of the event.

In general, there are three possible means of analysing extreme precipitation (Sevruk and Geiger 1981):

1. analysis of modeled time series,
2. analysis of the annual maxima series,
3. analysis of partial duration series.

The last-mentioned category also includes analysis of annual exceedance series which consist of the N largest values in the record, where N is the number of years of record.

A particular value of rainfall intensity always has a longer return period if derived from annual maxima series than it would have if derived from partial duration series. The difference between the results obtained from frequency analysis of the annual maxima series and those that are based on partial duration series has been shown to be small in respect to return periods extending over more than ten years (Cunnane 1973, Rosbjerg 1977). With regard to return periods of less than ten years, the differences are significantly large, however. With some assumptions, theoretical factors can be derived for converting values from the partial duration series to the annual series or vice versa (Chow 1964, Frederic et al 1977).

Analyses of partial duration series are mainly applicable to practical design purposes, as all short-term rainfall records are partial duration series.

Duckstein (Duckstein et al 1972) found that the return period of seasonal maximum point rainfall could be derived from the following event-based process, assumed to be valid for the summer precipitation season:

- the number of events per season is Poisson distributed,
- rainfall events are independent, identically distributed random variables,
- the volume of point rainfall per event is exponentially distributed,
- the number of events per season and the amount of rainfall per event are independent variables.

Those assumptions were used by Davis (Davis et al 1976) for deriving the probability density function of the return period by introducing an uncertainty of estimate into the parameters, calculating the expected value of the return period. When we know the uncertainty in the return period, expressed as a posterior probability density function, it is possible to generalize this approach so that it can be related to the return period of flows. This will allow the user to find the degree of sensitivity which is needed in

order to make design decisions, for example by applying the Bayesian decision theory. (Davis et al 1976).

Nguyen and Rousselle (Nguyen et al 1981, Nguyen 1982) emphasize that there is a lack of a generally acceptable procedure for the derivation of a synthetic temporal rainfall pattern. A stochastic model for the time distribution of hourly precipitation, proposed by Nguyen, can take into account the persistence of rainfall occurrences through first and second order Markov chains. The results obtained by using the second order model were not found to be significantly different from those that were received when the first order model was used.

The question of the interdependence of consecutive rainfall segments seems to be crucial with respect to the necessity of using higher order models. Where short-term rainfall series were concerned, this question was discussed by Hershfield and Engman (Hershfield and Engman 1978). The conclusions drawn from an analysis of about 100 storms are that there is no typical rain sequence, but there is a high autocorrelation for very short time lags. On the basis of the work done by Hershfield and Engman (Hershfield and Engman 1978), we may conclude that the correlation of incremental amounts in both time and space on the one hand and strong persistence in time of the short duration rainfall increments on the other must be considered in efforts to develop a synthetic design storm.

The question which distribution function fits best to extreme values of precipitation has been discussed for a long time. Since nature does not have to follow any theoretical distribution, there is a physical reason to believe that more than one statistical distribution can be fitted to different parts of the same precipitation series. This idea was tried by Jenkinson (Jenkinson 1955), who developed a statistical method which combines the emphasizing of the low probability part on the frequency distribution with an objective computation procedure. The application of

Jenkinson's method to the extremal distribution of low probability annual values of rainfall was studied by Samuelsson (Samuelsson 1972) and Krishnan and Kushwaha (Krishnan and Kushwaha 1975). Krishnan found that Jenkinson's method has a tendency to underestimate observed values. A development of the idea of using more than one distribution function can be found in a further work by Jenkinson (Jenkinson 1969). Another application of "combined distribution" by Ludwig (Ludwig 1979) indicates a possible solution to the problem.

At present, several distribution functions are used in estimating the extremes of precipitation; but the applicability of those distributions to different purposes has not been objectively established. Bearing this in mind, the WMO Commission for Hydrology, at its fifth session (1976), decided to appoint a Reporter on this subject. This resulted in an excellent report (Sewruk and Geiger 1981) reviewing the methods and results available concerning annual maxima series and partial duration series of point rainfall. The report is followed by comprehensive lists of commonly used methods of testing assumptions, choosing distributions, and calculating the parameters, as well as by an extensive list of references.

3.2 Spatial Distribution of Rainfall

3.2.1 General

In practical hydrological applications, hydrologists are seldom interested in the rainfall itself; it is usually the runoff and its consequences which are of main interest. As the rainfall measurements, apart from radar observations, give point values, and as the runoff is, by its very nature, an areal process, an assessment of areal rainfall values is needed if we want to use rainfall to predict the runoff. The rainstorms can move across the catchment, and the speed and direction of that movement is significant to the shape of the runoff hydrograph. Moreover, antecedent precipitation conditions within the catchment differ from storm to storm, influencing the amount of runoff.

Both rainfall movement and its areal distribution, have to be included, preferably on a statistical basis, in a description of the rainfall. The significance of moisture conditions for the runoff has been studied by several researchers, see for example (McPherson 1975, Urbonas 1979). Thus, the studies concerning the spatial distribution of rainfall generally include two main fields: generating the areal rainfall from the point measurements, and investigating the dynamic properties of the rainfall. The first category includes interpolation and extrapolation techniques, the development of areal reduction factors, and the generation of rainfall fields by deterministic or stochastic models. The second category includes hydrometeorological studies of storm-generating mechanisms as well as methods of calculating the speed, the direction, and the size of the rainfall cells.

Figure 3.4 supplies an attempt to systematize possible ways of analyzing rainfall data when more than one gauge are available.

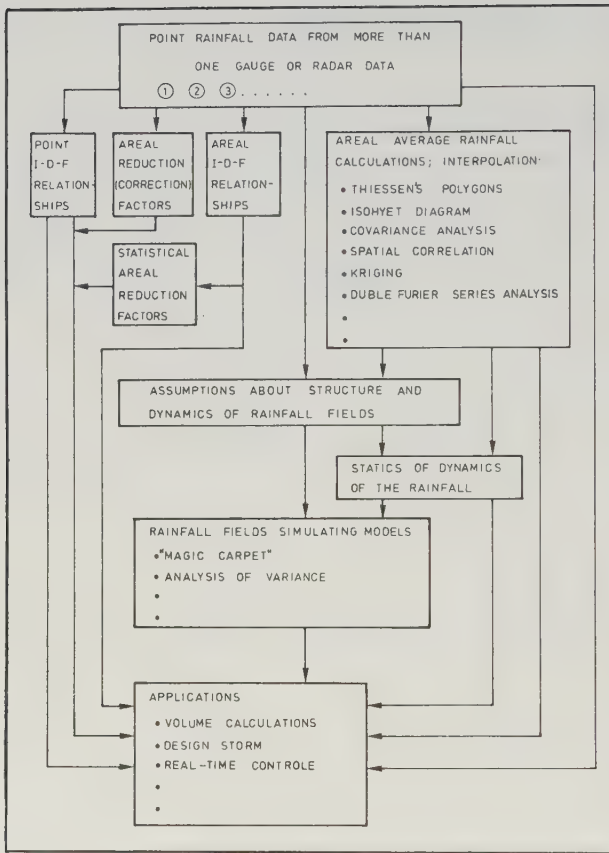


Figure 3.4 Analysis of areal rainfall data

3.2.2 Methods of Extrapolation

Neither the intensity nor the volume of the rainfall is ever uniformly distributed in space. If rainfall data are available from more than one gauge, point values can be extrapolated to areal values; the extrapolated values will provide a better approximation of real areal rainfall than data from one gauge. Interpolation between point rainfall values and extrapolation to areal values can be performed in different ways. Traditional methods of extrapolation are: arithmetic average, Thiessen polygons, and the izohyetal method. All these methods produce a weighted mean over the

point values. The only difference between the methods is the choice of weighing coefficients. With regard to non-uniformly distributed variables like precipitation, none of those traditional methods reduces the uncertainty in a calculated areal mean value, since the true value between observation points is never known. The only reason to choose more sophisticated methods is to adapt the method to computerized calculation techniques using objective criteria. The validity of the results also depends on the chances of being able to assess the confidence limits of the extrapolated output.

The question of the reliability of interpolated values was investigated by Kelway (Kelway 1974). The "true values" of areal rainfall were taken from synthetic rainfall patterns thought to be typical of those likely to occur in nature. The errors occurring due to interpolation were analyzed and expressed by means of regression equations on variables describing the rainfall pattern. A comparison of errors due to the interpolation technique was made by Gottschalk and Jutman (Gottschalk and Jutman 1982). Mean interpolation errors were compared with the aid of the arithmetic mean, Thiessen polygons, and the correlation method. The errors appeared to be slightest when correlation was employed, but differences between results did not exceed 5%.

The most common method of computerized interpolation is based on the spatial correlation function. Traditionally, the interstation correlation function was used to assess the necessary spacing between gauges in order to achieve reasonable areal values. The conclusions of those studies can be summarized as follows: the spatial correlation pattern varies with the geographical situation, the type of storm, the season of the year, and the time of averaging. (Huff 1979, Osborne et al 1979, Rodrigues-Iturbe and Meija 1974a, Sharon 1972). Necessary spacing between gauges decreases with the time of rainfall averaging. In the case of short-term rainfalls of the convective type, and with one to ten minutes of averaging, the average size of the rainfall cell is reported to vary between 1 and 5 sq.kms. in diameter.

According to Huf (Huf 1979), a gauge spacing of 1.8 kms. will explain 90% of the variance in spatial rainfall on a monthly basis. Osborne (Osborne et al 1979) shows that for 15-minutes max rainfall and for correlations higher than 0.9, the spacing between gauges must be as short as 300 m. Felgate and Read (Felgate and Read 1975) have used the concept of the "characteristic ellipse", defined as a smoothed iso-correlation line on the 0.5 level, to describe a rainfall pattern. The average size of the "characteristic ellipse" for 2-minute raincell was found to be 2.8 by 1.3 kms. No attempt was made to assign any rainfall intensity to this ellipse. A rainfall size characterized by an 0.7 iso-correlation line varying between 0.8 and 2.0 kms. in diameter was reported from Sweden (Niemczynowicz and Jönsson 1981a, 1981b).

More recent applications of the correlation structure deal with developing areal rainfall values. Gottschalk and Jutman (Gottschalk and Jutman 1982) have developed a method of calculating the weighing coefficients for point measurements, using a correlation structure. The method is well suited to automatized computation.

In the applications described above, the correlation functions were determined empirically, from the diagram of correlation coefficients plotted versus interstation distance. Other researchers prefer to develop the correlation function analytically and then apply it to real observed data. Stohl (Stohl 1981) has developed a method of determining the correlation function analytically on the basis of the storm model function. The results have to be tested on real storms; but the method seems to pave the way for the development of a complete stochastic model producing areal rainfall patterns - a model which can be employed in practical applications.

During recent years, a "kriging technique" formulated by Matheron (Matheron 1969, 1970) has frequently been used as an interpolator based on the stochastic approach. The work done by Gambolatti and Volpi (Gambolatti and Volpi 1979)

and by Chua and Bras (Chua and Bras 1982) should be mentioned in this context. The conclusion which can be drawn from the application of kriging to the interpolation of rainfall data is that the main advantage of using this method rather than any other consists in its ability to provide an assessment of the interpolation error. It cannot be proved, however, that this technique is more reliable than other methods.

Other computerized interpolation techniques are based on trend surface analysis, which involves fitting a two-dimensional polynomial function to the data points. Alternatively, a double Fourier series is used; its advantage as compared to the polynomials is that matrix condition problems do not arise (Thorpe et al 1979). Those techniques appear to be the most promising ones when it comes to developing stochastic models for areal rainfall. The works presented by Hall and Barclay (Hall and Barclay 1975), Edwards (Edwards 1972), Thorpe (Thorpe et al 1979), and Schagen (Schagen 1980) have to be mentioned in this context.

3.2.3 Area Reduction and Correction Factors

The interpolation techniques described above require the availability of data from more than one gauge. In practice, however, only one gauge with a sufficiently long observation series is often apt to be available. Additional information from other sources than the gauge will have to be supplied in this case, if the rainfall input is to be improved. This additional information is usually taken from other locations, assuming that this information is also valid for the catchment in question.

A number of different depth-area relationships, known as area reduction factors (ARF-s) or area correction factors (ACF-s), have been developed in different countries. Two types of depth-area relationships are usually distinguished: storm centered and fixed area ARF-s. Only fixed area ARF-s, defined as the ratio between areal and point rainfall with

the same return period and for the same area, has any hydrological meaning in cases where frequency estimates are to be made. ARF-s have been used in USA for a long time (U.S. Weather Bureau 1958). Relations derived by the U.S. Weather Bureau, and discussed by Rodriguez-Iturbe and Meija (Rodriguez-Iturbe and Meija 1974b), were recently improved by Mayers and Zehr (Mayers and Zehr 1980). In the U.K., similar work has been done by the Flood Studies Group and improved by Bell (Bell 1976). Nguyen and Rouselle (Nguyen and Rouselle 1981) have proposed the theoretical methodology of deriving the areal correction factors on the basis of frequency analysis of point and areal rainfall data. By means of comparing point and areal frequencies, an areal correction factor which was greater than one was obtained.

Most of the above-mentioned studies deal with rainfalls of long durations and areas ranging from some hundreds to thousands of sq. miles, which is not adequate for most of the urban hydrology applications. Studies on a smaller spatial and temporal scale, more adequate where urban problems are concerned, have been carried out in Sweden. Areal intensity-duration-frequency curves and statistical areal reduction factors were developed for a rainfall duration ranging from 1 to 40 minutes, and for areas of up to 25 sq. kms. (Niemczynowicz 1982a, 1982b, 1983a). Conclusions from the Swedish studies confirm the findings of Nguyen and Rouselle (Nguyen and Rouselle 1981) that ARF-s really depend on the return period.

On the basis of the reported studies, one general conclusion can be drawn: considering the lack of fully developed and experimentally justified models for transferring point rainfall to areal rainfall, it is advisable to use the ARF-s if the drainage area is bigger than 25 sq.kms. (Yen and Chow 1980). This conclusion was confirmed by others (Abraham et al 1976). Studies performed in Sweden (Niemczynowicz 1982b) suggest that it is advisable to use the ARF-s even on catchments smaller than 25 sq.kms.

3.2.4 Structure of the Rainfall Pattern

As most of the interpolation techniques and rain field generating models are based on subjective assumptions and verbal descriptions of the rainfall process, knowledge of the real features of the rainfall pattern associated with the distinct genetic process is very important (Amorocho 1981).

Most of the recent developments in rainfall pattern recognition and in studies of rainfall-producing mechanisms are indebted to works done by researchers in hydrometeorology. The works of Schlesinger (Schlesinger 1978, 1980) and Blechman (Blechman 1981) provide a foundation for the basic understanding of the mechanisms involved in thunderstorm generation. Several researchers distinguish between convective storms of the so-called "air mass" type and extra-tropical cyclonic storms with a banded structure parallel to the fronts (Amorocho and Wu 1977, Amorocho 1981).

Precipitation areas have often been classified and subdivided according to their horizontal extension (Gupta and Waymyre 1979). According to Austin and Houze (Austin and Houze 1972), so-called synoptic areas with an extension greater than 10 thousand sq.kms. usually contain large meso-scale areas (LMSA), also called "bands", ranging in extension from 100 to 1000 sq.kms. LMSA are characterized by their own movement within synoptic areas and by the content of smaller mesoscale areas (SMSA), or of clusters of "convective raincells". SMSA extend from 10 to 100 sq.kms., raincells from 10 to 30 sq.kms. All structures within the synoptic area possess their own motion, development, buildup and decay. The life span of those structures decreases with their extent. Precipitation intensity within the smaller structures is always higher than the intensity in the region surrounding it.

Many recent studies suggest that the extent of the raincells is much smaller than was suggested above. The size of the separate raincells, as reported in the relevant literature,

seems to diminish in proportion to the spacing between the gauges used in the investigation. This implies that smaller structures could perhaps be found within previously recognized raincells. It is essential for the general understanding of rainfall processes that those fine structures of the rainfall pattern will be studied.

Another interesting question is whether the mechanism producing the raincells and their cellular structure is similar in different geographical locations. Recent developments in radar observation techniques and the use of remote sensing; including the infrared channels of satellite images, can improve our knowledge about the real shape of the raincells and the structure of the rainfall field (Kruger and Shultz 1982, Atmanspacher and Shultz 1981, Hildebrand et al 1979, Changnon and Vogel 1980). The radar observations are used for quantitative rainfall measurements, allowing more insight into the spatial and temporal rainfall distribution (Einfalt and Schilling 1984). The rainfall data obtained from radar observations are used in short-term rainfall forecasting models applied to real-time flow control in sewage networks (Schilling 1984a, 1984b).

3.2.5 Models for Generating Rainfall Fields

Early models for rainfall-field generating usually possessed poor foundations with regard to their respective observation bases. The fundamental approach was to use a mathematical description of a stochastic process based on rather general understanding and recognition of the main rainfall structures. As the amount of data increased, the models became more closely related to the natural precipitation process. The basic assumption used by many researchers is that the rain variations might form a random field.

One of the best-known models to be based on this assumption was formulated by Amorocho and Slak (Amorocho and Slak 1970) and Amorocho and Wu (Amorocho and Wu 1977). In this model, rain fields within the small mesoscale area are simulated

for a rectangular grid in which elliptic raincells are born, grow, decay and die. The centers of the grid are occupied by raincells with a randomly given age, or they remain empty. The centers of the grid travel over the ground as the cells go through their life cycle (Amorocho 1981). The model is not strictly stochastic; once initiated, the rainfall field only contains fixed periodic elements. This model, cited as a "magic carpet", was later modified to form the so-called Amorocho-Lloyd-Pawitan (ALP) model (Lloyd 1978, Pawitan 1980).

Bras and Rodriguez-Iturbi (Bras and Rodriguez-Iturbi 1976) assumed that the rainfall intensity field is Gaussian, as the covariance function of the field should be Gaussian in order to satisfy Taylor's hypothesis of turbulence. Following the physical description of the rain field structure, Gupta and Waymyre (Gupta and Waymyre 1979) assumed that it should, from the mathematical point of view, be represented by two auxiliary stochastic fields. The first one, representing the birth of cells in space and time within a moving mesoscale area, should be realized as a Poisson field with a stochastic mean value function. The second field represents the number of cells which contribute to the rain within the cluster. The evolution of this field in time is a non-Markov stochastic process. The mathematical description following these assumptions forms a complete stochastic model reproducing rainfall intensity fields. Those mathematical constructions should be tested on real data before the various assumptions can be justified.

Another group of rainfall field generating models was developed from a well-known statistical procedure called analysis of variance (Clarke 1972, Abraham et al 1976, Sieker 1977, 1980). The three fold analysis-of-variance model developed by Sieker (Sieker et al 1976) was used to develop a time and spatial variable design storm pattern for the city of Hamburg and for the reconstruction of selected historical events under forecasting conditions (Sieker 1980).

Most of the existing models can reproduce a rainfall field on a relatively large scale. However, this coarse scale is not adequate for application to urban hydrology. To our knowledge, there is at present no model which can reproduce the fine structure of a rainfall field and take the dynamical characteristics of the storm, into account.

Now, that we are facing the increasing complexity of the modern stormwater systems, it appears more and more desirable to use automatic control to allocate the hydraulic resources of the system. The performance of automatic control systems depends on the ability to predict the spatial rainfall rates with the aid of the used model. A number of models adapted to automatic control systems have been developed recently (Nguyen et al 1978, Johanson and Bras 1980, Sieker 1980, Schilling 1983).

3.2.6 Dynamics of Rainfall Fields

It is generally accepted that the shape and the peak of the runoff hydrograph depend on the shape, speed and direction of raincell movement in relation to the direction of the main watercourse in the catchment (Surkan 1974, James and Robinson 1982, Niemczynowicz 1984b, 1984c). This statement implies that the rainfall dynamics should be included in a rainfall field generating model on the probabilistic level. The question arises if the direction of the rainfall movement is a random variable, and how it is distributed.

Experimental evidence proves that there are some prevailing directions of rainfall movement that are typical for the region (Raudkivi and Lawgun 1974, James 1981). Several researchers have found good correlation between the wind direction at 700 mb height and the direction of the raincell movement (Shearman 1977, Wickerts and Granath 1979). This provides the first possible way of treating the rainfall direction statistically. The other way is to extract information about the rainfall velocity and direction from the measurements themselves.

The known methods of tracking raincells can be roughly divided into three groups: center of gravity methods, three-point methods, and inter-station correlation methods. A simple center of gravity method usually predicts the direction well, but is rather dubious where speed prediction is concerned. The three-point method, based on customary triangulation, produces velocity vectors for all combinations of three gauges. The method requires a rather subjective determination of the characteristic rainfall patterns, for example the time of the storm arrival, or the time to peak (Hindi and Kelway 1977, James and Scheckenberger 1982, James and Robinson 1982, James and Scheckenberger 1983, Shaw 1983).

A method of storm tracing known as "full correlation analysis" was developed by Briggs et al (Briggs et al 1950) and extended by Philips and Spencer (1955), Fooks (1965), Fedor (1967) and Felgate and Read (1975). The analysis involved the calculation of three cross-correlation functions between the gauge records taken in pairs; the correlation coefficient was computed as a function of a relative time shift introduced between the two records. The three cross-correlation functions, the mean autocorrelation function, and the gauge coordinates were then used to calculate the storm velocity pattern.

Another method developed by Marshall (Marshall 1977, 1980) and employed by others (Sherman 1977, Niemczynowicz and Jönsson 1981b) uses cross-correlation between all pairs of raingauges with different time lags. The Marshall method is based on the approximation that the storm field is isotropic, i.e. the rainfall at any given distance from the centre of the rain is independent of direction. This assumption is not true if the distance between the gauges is of the order of 1 - 3 kms.

Most of the methods seem to work well for single-peak rainfall events, but often fail when more than one raincell are present over the gauge network at the same time. When one

employs simpler methods like center of gravity or isohyetal analysis, a lot of subjective judgement is required. The correlation methods are more objective and are suitable for computerized calculations. It is evident that information about the rainfall movement exists in a set of rainfall data from a dense network. Studies made in Sweden (Niemczynowicz and Dahlblom 1984) showed that this information can be extracted from the data by means of relatively simple procedures. However, there is still a lack of studies in which the errors of different rainfall-tracking methods would be objectively compared.

4. MEASUREMENTS OF RAINFALL INTENSITIES IN LUND

This chapter presents the equipment used for rainfall measurements in Lund as well as the methods used for data collection and data processing.

This chapter is, to a major extent, based on the following publications:

Falk, J, Jönsson, O, Niemczynowicz, J (1979): "Measurements of Rainfall Intensities in Lund". Department of Water Resources Engineering, Lund Institute of Technology, University of Lund, Report No 3023.

Niemczynowicz, J, Grahn, L (1981): "Hydrological Instrumentation". Department of Water Resources Engineering, Lund Institute of Technology, University of Lund, Fifteenth Anniversary Report, No 3053.

4. MEASUREMENTS OF RAINFALL INTENSITIES IN LUND

4.1 Introduction

Precipitation is the most important factor governing the urban runoff pattern. What is needed at the present time is information not only on temporal but also on spatial variations in rainfall intensity. Accurate input data in this area are essential to effective economical and physical planning as well as to the implementation and evaluation of urban storm water systems. Unfortunately, there are not many rain-gauge networks with sufficient density and accuracy of registration for resolving the spatial and temporal variations of short-term rainfall intensities. The time-scale range which is adequate for urban hydrological problems is measured in minutes. The space scale of the rainfall pattern which influences the urban runoff is of the range of the extent of single rainfall cells. Hence, the spacing between the gauges and the time resolution of the registration must fit these time and space scales.

A research project aiming to explain spatial and temporal variations in rainfall intensity with regard to short-term rainfalls in Lund started in 1978. In order to satisfy the requirements of the project, a special data collection system which can deliver high-quality data with good time and space resolution has been developed. Twelve raingauges have been installed to cover an area of 25 sq.km. in the central part of Lund. The network was meant to be as regular as possible; but the final space distribution of the gauges over the city is not as even as could be desired, due to limitations in the possible choice of locations. The average distance between the gauges is 1.3 km. Figure 4.1 shows the map of the rain-gauge network. Appendix 1 contains photographs of the twelve gauges on their locations.

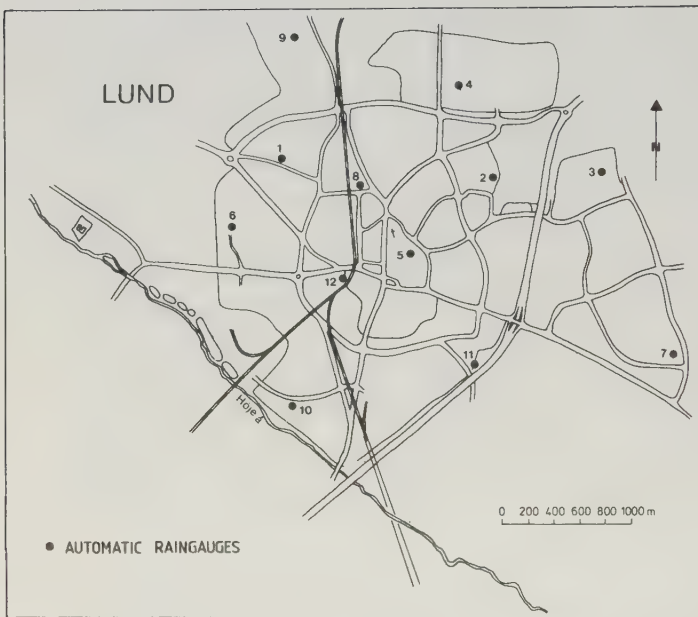


Figure 4.1 Raingauge network in Lund

4.2 The Raingauge Network in Lund

When the project started, there was no raingauge available on the market that could meet the requirements: high accuracy and low price. The decision was then made to develop and manufacture a gauge within the Department of Water Resources Engineering.

The gauge works on the tipping-bucket principle, which makes digital readings possible. The volume resolution is, as an average, 0.035 mm per one tipping with a funnel area of 428 sq. cm, allowing rainfall intensities between 0.035 and 4.2 mm/min to be measured. Figure 4.2 shows the complete gauge, whereas Figure 4.3 shows the pulse-generating unit.

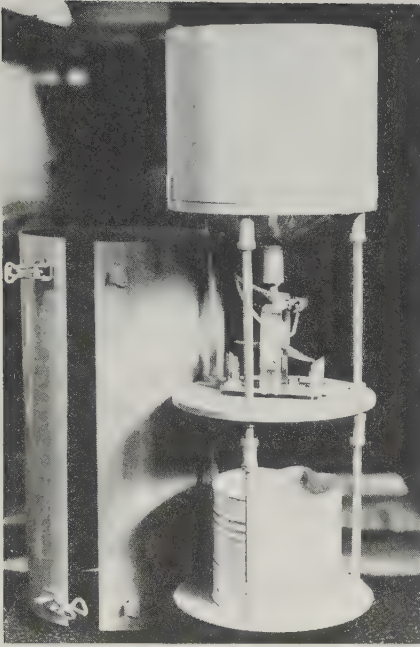


Figure 4.2 Raingauge developed at the Department of Water Resources Engineering

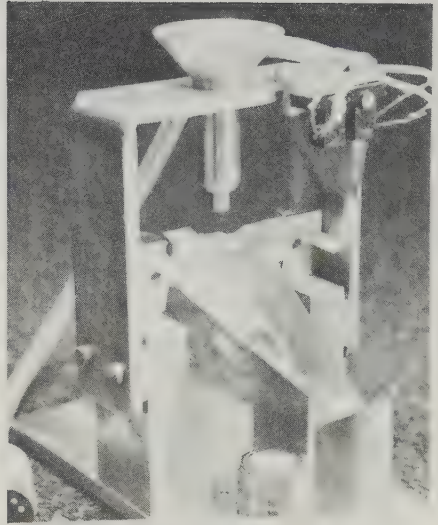


Figure 4.3 Pulse-generating unit

The funnel, turned from stainless steel, is 205 mm high. In spite of the efforts undertaken in manufacturing, the diameters of the funnels could not be made exactly the same for all gauges. This has entailed a variation with regard to the catch area of between 425.5 and 429.7 sq.cm. This is, however, taken into account in an individual calibration of the gauges. The shape of the drop former is designed in such a way that a nearly constant drop volume is achieved for all rainfall intensities within the measuring range.

The shape of the bucket is designed in such a manner that the relationship between the volume per tipping and the rainfall intensity is as close to being linear as possible. There are two different factors which are important in this context:

- A. the tilting time must be as short as possible in order to minimize the volume of water entering the bucket during the tilting.

- B. the evacuation of the bucket must be close to complete during a short increment of time, before the other bucket is ready to tilt.

The problem presented in A. is solved by the design of the bucket, which allows the mass centroid of the water to move rapidly towards the edge of the bucket during tilting. The result desired in B. is achieved by taking advantage of capillary forces. The edges of the bucket and the pillars supporting it have capillary splits. When the bucket strikes upon the supporting pillar, the capillary suction from the splits in the pillar sucks the bucket dry in less than one second.

Efforts to make all the buckets identical were made during manufacturing, but the average volume per tipping nevertheless varies from 0.0315 to 0.0417 mm for the twelve gauges. A careful dynamic calibration of each individual raingauge was performed in the laboratory of the department. A constant rainfall intensity was supplied to the gauge, and the volume of water which passed the gauge was measured after about 200 tiltings. In this way about 25 different rainfall intensities within the measuring range were tested, each of them giving one point on the calibration diagram. In spite of all measures taken to avoid nonlinearity, all the gauges show a slightly nonlinear relationship between number of tippings per time unit and rainfall intensity. Figure 4.4 shows an example of calibration curve. The nonlinearity is insignificant up to a rainfall intensity of about 1.8 mm/min, but with higher intensities it must be taken into account.

The calibration curve obtained by means of regression analysis which best fits the calibration points can be expressed by the following nonlinear relationship:

$$I = a A^b$$

where:

I - rainfall intensity mm/min
 A - number of tippings per minute
 a, b - parameters

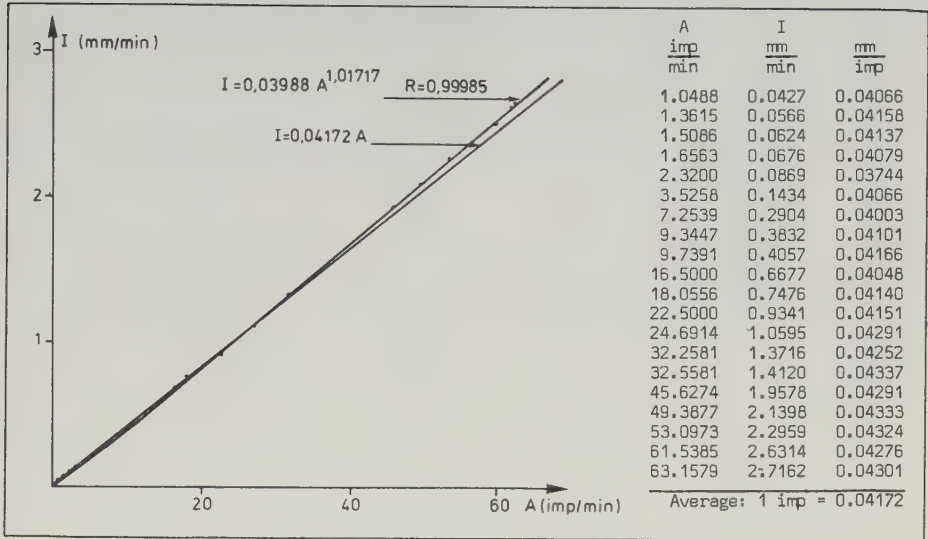


Figure 4.4 An example of a calibration curve for a rain gauge

Table 4.1 supplies the values of parameters a and b , the average tipping volume, and the correlation coefficient between the number of tipplings per minute and the rainfall intensity for twelve gauges.

A special control routine for checking the stability of calibration parameters in the field was developed. A well-defined volume of water was poured into the funnel, the intensity changing gradually in order to simulate the whole range of rainfall intensities from 0.035 to 3.5 mm/min. The known volume of poured water was compared with the volume calculated by means of the calibration curve. Corrections of calibration were made if the volume error was higher than 1%. A field calibration procedure and gauge cleaning were usually performed once a week.

Table 4.1 Calibration parameters for the raingauges

Gauge No	a	b	Correlation coefficient	Average volume per tipping, mm
1	0.0358	1.0346	0.9997	0.03898
2	0.0334	1.0434	0.9998	0.03861
3	0.0366	1.0298	0.9998	0.03994
4	0.0364	1.0289	0.9998	0.03928
5	0.0375	1.0305	0.9998	0.04110
6	0.0357	1.0202	0.9998	0.03762
7	0.0321	1.0494	0.9999	0.03659
8	0.0323	1.0513	0.9995	0.03723
9	0.0294	1.0476	0.9996	0.03311
10	0.0399	1.0172	0.9999	0.04172
11	0.0350	1.0200	0.9995	0.03779
12	0.0294	1.0256	0.9986	0.03150

After a dynamic calibration of carefully manufactured rain-gauges had been performed, several differences between the gauges were found, and the nonlinear characteristics of the calibration curves were proved. At this point, it becomes pertinent to ask whether raingauges available on the open market also show individual differences and a nonlinear calibration curve. In order to answer this question, a similar calibration procedure was applied to a 0.2 mm raingauge of the RIMCO type, manufactured in Australia. A slight non-linearity in gauge response was found in respect to intensities above 2 mm/min. This implies the conclusion that in order to avoid unnecessary errors in rainfall measurement, all gauges of the tipping-bucket type should be subjected to individual calibration.

4.3 Data Collection System

When the raingauge network and the data collection system in Lund were being designed, it was assumed that good accuracy of data is a necessary condition if studies of the areal and dynamic properties of rainfall are to be feasible. In order to

ensure that the rainfall data are satisfactory, readings of individual raingauges in the field must be transmitted to the point of registration without additional errors and time inaccuracies. The registration of readings from individual raingauges must make sure that the best possible time synchronization between the gauges is achieved. Registration should preferably be made in computer compatible form. In order to meet the requirements, a special data collection system has been developed.

The data collection system is shown schematically in Figure 4.5. By means of an underground cable, each of the twelve raingauges is connected to a transmitter situated in the nearest house. The transmitter transforms a single electric pulse from an optical source-detector array of a tipping to a sinusoidal

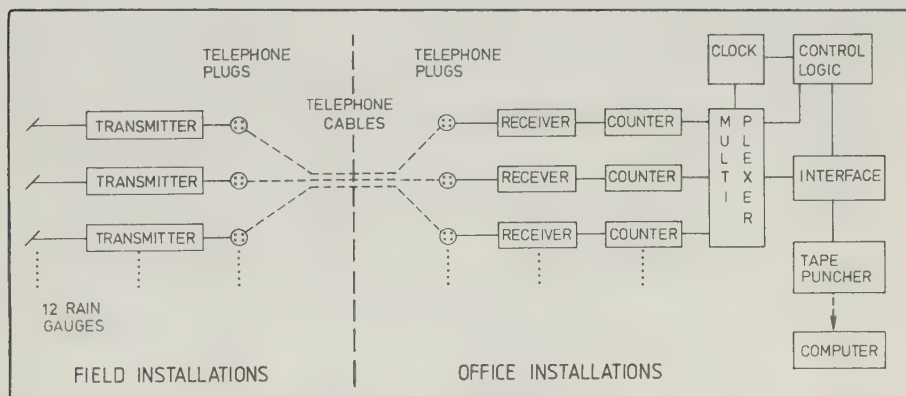


Figure 4.5 Data collection system for rainfall records

tone burst with a frequency of 967.5 Hz and a length of 0.25 s. The signal is transmitted on leased open telephone lines to the receiving station in the office. The receiver is selective and produces an out signal only when receiving a pulse of 967.5 Hz having a length of at least 0.2 s. These signals are counted, and the number of pulses during a preset time period is recorded on a tape puncher for all gauges. A recording of readings from all gauges takes place for each time period during which at least one gauge has counted at least one pulse.

For each recorded time period, a day number and time from a digital clock is registered, ensuring an absolute time synchronization between the gauges. The recording interval is set to one minute, but can easily be changed to a shorter period if desired.

4.4 Data Processing System

According to the planned length of the project, the raingauge network would be in constant operation during at least three years. The number of single readings of one-minute values of rain intensity could amount to about 5 million during three years of operation. In order to handle this great amount of data, a special system of data storing and processing has been developed. Figure 4.6 shows a schematic representation of the data processing system.

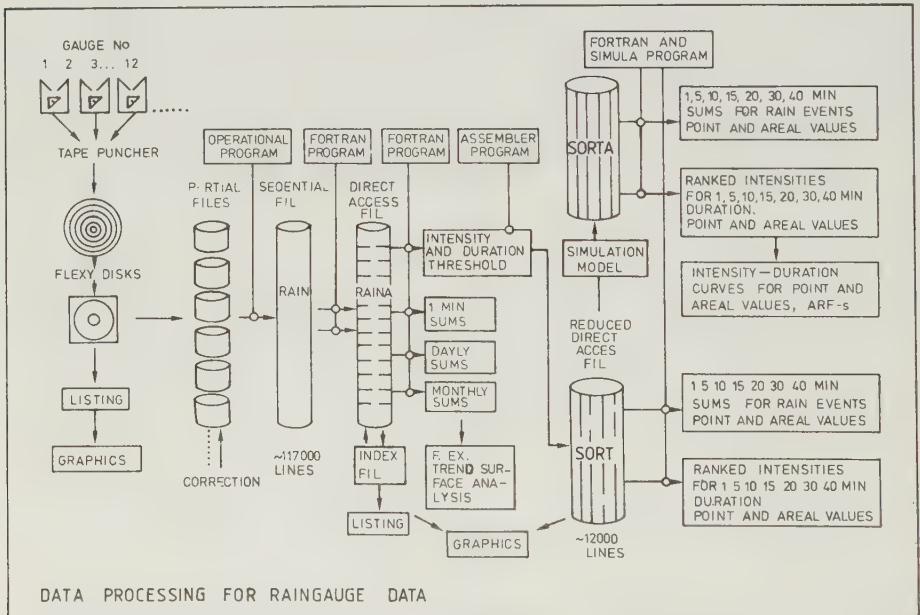


Figure 4.6 Data processing system for rainfall records

The raingauge readings consist of two-digit numbers representing the number of pulses per minute, but rainfall intensities calculated via a calibration function can have six digits. However, since it is desirable to save data which have not been manipulated, it was decided that all data will be stored as original two-digit records. Calculation of rainfall intensities is done as a last step of processing, usually on reduced data. The original data are stored on paper tapes, each tape containing between one week and three months of records, depending on the frequency of the rain. Numbered paper tapes are read on a NORD-10/s computer and transferred to disks. The first corrections of obviously erroneous records can be performed at this stage. Data from disks are transferred to the mainframe UNIVAC-1100 computer, creating a number of primary data files labeled with original numbers of paper tapes.

When three years of data had been collected, the amount of data was considered sufficient for a further statistical analysis. A number of Fortran programs have been developed in the creation of different data bases necessary for different applications. Primary files are merged into a sequential file called RAIN and a direct access file called RAINA. A number of interactive Fortran programs can be applied to the RAINA file for listing and plotting the required segments of data. Further corrections of erroneous data can be made at this stage. Rainfall volumes for different time periods, from one minute to one year, are calculated and written on a file called INDEX, which can be used for different statistical calculations. An Assembler program applied to the RAINA file produce a reduced field of data by excluding all values below a preset threshold of rainfall intensity and duration. A new direct access file called SORT, containing a reduced field of data, is produced. Since the interest was focused on high-intensity rainfalls, the threshold level employed in this context was established at 15 pulses during 15 consecutive minutes. Rain intensities below 2 mm/hour were excluded, which reduced the data by about 75%, but the total rain volume was only reduced by 5%. The level of the threshold can easily be changed if required.

The SORT file still consists of two-digit data and is relatively easy to handle and inexpensive to store on a direct access file system. All other files are stored on magnetic tapes. All programs producing INDEX file can also be applied to the SORT file, to create different, specially designed, data bases for different applications.

Due to malfunction of the gauges there are gaps in the record. In order to replace missing values, a routine for distinguishing them from zero values has been developed. The function of the gauges was tested during spatially uniform rainfall events classified as "frontal rains". The criterion of rain-type classification was arbitrarily chosen as a certain relation between rainfall intensity and duration. If one particular gauge shows zeroes during frontal rain, malfunction was assigned to this gauge and a "minus sign" has been entered in the INDEX file in place of the original data for this gauge and the rainfall event. If only zero values have been observed for this gauge during "convective rain" between two "minus signs" in the INDEX file, the malfunction of the gauge is also assigned to this rainfall. If more than 5 gauges are labeled as malfunctioning during the same event, the whole event is rejected. After this procedure of checking the functioning of the gauges, missing values were replaced by an interpolation procedure. A new file called SORTA, containing the complete field of data, was created. Much of the data processing procedure has been developed by G Svensson, University of Lund, as part of his work for his master's degree (Svensson 1983).

A number of graphical programs can be applied to all the files containing original, reduced or reduced and completed data. An example of a three-dimensional plot of rainfall intensities taken from the data base is shown in Figure 4.7.

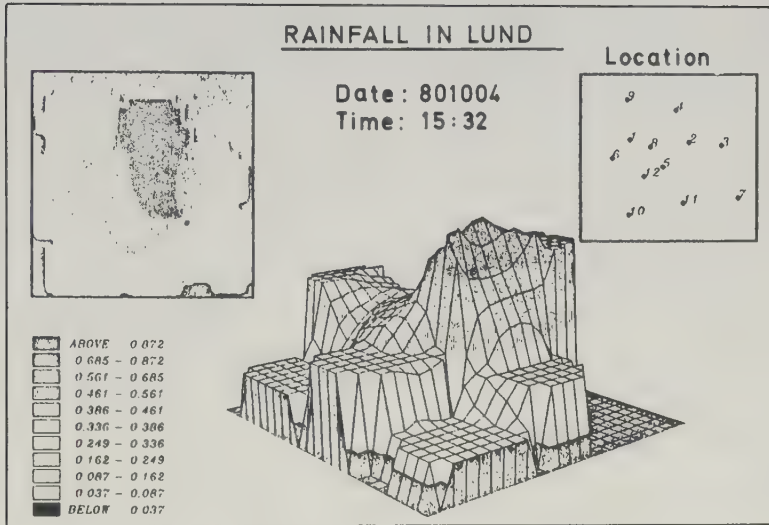


Figure 4.7 An example of graphical presentation of rainfall intensities in space by a color plot program

5. EXTREME RAINFALL EVENTS IN LUND 1979-1980

This chapter presents an analysis of the extreme rainfall events observed in twelve raingauges in Lund during a period of two years. To a major extent, it is based on the following publications:

Niemczynowicz, J, Jönsson, O (1981): "Areal Variability of Rainfall Intensity". Department of Water Resources Engineering, Lund Institute of Technology, University of Lund, Fifteenth Anniversary Report, No 3053.

Niemczynowicz, J, Jönsson, O (1981): "Extreme Rainfall Events in Lund 1979-1980". Nordic Hydrology, 12, (129-142).

5. EXTREME RAINFALL EVENTS IN LUND 1979-1980

5.1 Introduction

All raingauge measurements state one-point values. The rain-gauge only represents its own funnel area; all areal estimates of rainfall volumes or rainfall depth are more or less erroneous. The practical applications of rain data always involve areal measures; the knowledge of the areal distribution of rain thus becomes very important for the correct evaluation of rain volumes (Bell 1976). This fact is generally accepted, but not much has been done in the way of employing correct, areal measures of rainfall in practical applications. Perhaps the reason is that mere one-point rainfall statistics are complicated enough; besides, the areal statistics, according to general belief, will not be all that different from one-point rainfall statistics where very long time series are concerned.

During the recent decade, computerized modeling of rainfall-runoff relations has been applied much more frequently than before. In many urban areas, the use of modeling is the only reasonable way of achieving an economical solution of various water management problems such as the design of new sewage networks, or the renewal of old stormwater systems. Two types of rainfall input data to urban runoff simulation models are generally used: design rainfall hyetographs and long historical rainfall records (Marsalek 1978, Arnell 1978). The use of historic records is suitable for solving many urban water problems; it is useful when studying volumes of combined sewer overflows, flooding, pollution control etc. (Colyer 1978). The third type of rainfall input data should be recognized too: it is the observed single rainfall event during which the consequences - such as runoff excess or pollution loads - have been observed. The return period for such an event is usually unknown or can only be roughly estimated by comparison with i-d-f curves, assuming that such curves are available.

Single-event hyetographs are frequently used in the calibration of rainfall-runoff simulation models in order to achieve

the best possible agreement between observed and simulated runoff hydrographs. The single-event hyetographs have also been used for simulating changes in the urban water system and assessing their consequences in terms of storm water shock loads and volume of combined sewer overflows (Hogland and Niemczynowicz 1980).

It has previously been recognized that the use of historical storms calls for more local field data than the use of design storms (Sieker 1978). But if a single storm is employed in the simulation of the runoff hydrograph, and the results are to be generalized in statistical terms, a good characterization of the spatial properties of this event is necessary. Not only the depth and volume of the areal rainfall are required, but the shape, size and movement of raincells, too, as well as knowledge of how these properties depend on the specific meteorological situation. In this case, the need for local field data is very extensive.

Unfortunately, there are only few measurements of short-term rainfall in urban areas with good spatial and time resolution. No other measurements will do when it comes to making a description of raincell characteristics and movement possible.

The raingauge network operating in Lund since 1978 delivers the rainfall data which supply the opportunity of studying the short-term rainfall intensities within a single city in connection with the specific meteorological situation. The size, shape and movement of the raincells were investigated with regard to ten extreme rainfall events. The arbitrary criterion for the selection of the events was set at a maximum of 10 minutes average intensity observed for any of the twelve gauges. The observation period started in June 1978 and ended in September 1980.

The point and areal intensities of ten extreme events are presented. Storm-centered Areal Reduction Factors (ARF) were calculated for these ten events and for all gauges. The size, shape and movement of the raincells were discussed within the context of the observed meteorological situation.

5.2 Meteorological Context of the Extreme Rainfall Events

Two general rain-producing mechanisms are usually distinguished: macro-scale mechanisms, such as cyclones and anticyclones which express themselves in great horizontal and vertical transport and exchange of air-masses; and the meso-scale mechanisms. The latter produce meso-scale raining units (or convective rainfall cells) and usually appear as passing showers in the rear of extra-tropical cyclones or as local Cumulonimbus clouds inland; they can also occur around certain kinds of cold fronts and in tropical cyclones (Bergeron 1978).

The average yearly precipitation in Lund amounts to about 650 mm. The major part of this amount falls during the late summer and autumn in connection with the passage of frontal zones. The frontal rainfalls are usually of many hours' duration and relatively low intensity.

It has previously been observed that even these frontal cloud-systems are often characterized by a "granulated" and partly convective structure in respect to the precipitation pattern (Bergeron 1978). These "partly convective" storms were also observed in Lund with short, high intensity periods overlapping long periods of low intensity. But the most important rainfall systems producing all the ten extreme events presented, are meso-scale units, which often express themselves in thunderstorms.

Figure 5.1 shows the average daily precipitation amounts from 75 years of observations in Lund. The highest daily rainfall volume, about 4 mm/day, can be observed in summer during July and August. Figure 5.2 shows the standard deviations of the daily precipitation values calculated from 75 years of data. The highest standard-deviation values can be observed during July, which suggests that the greatest number of convective storms occur during that month. The absolute maximum of daily rainfall volume during 75 years in Lund was 81.8 mm, observed in July, 1941.

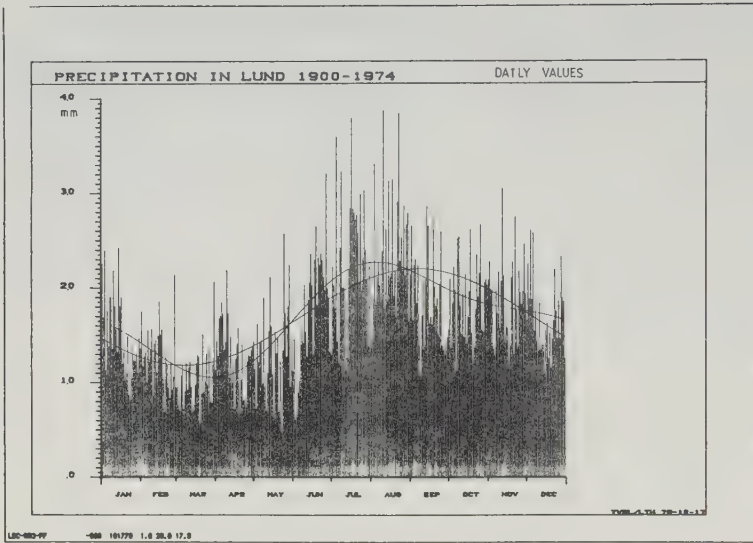


Figure 5.1 Daily averages of precipitation in Lund based on 75 years of data

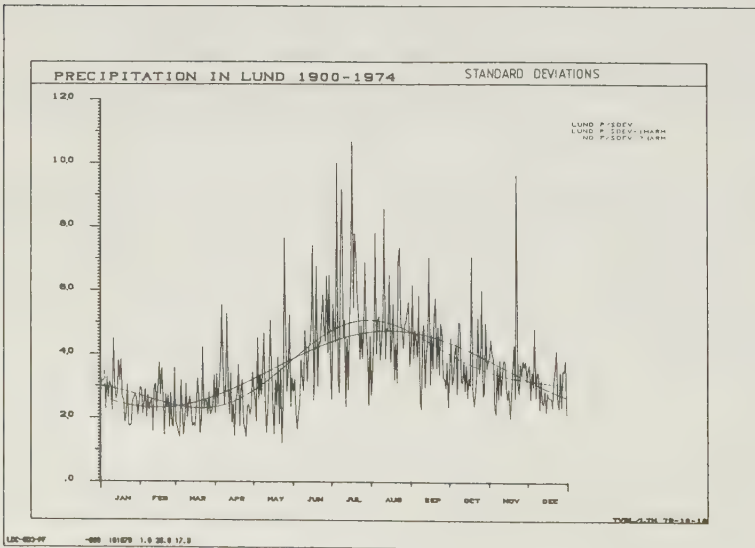


Figure 5.2 Standard deviations of daily averages of precipitation in Lund based on 75 years of data

A marked local variation in rainfall depth was observed in Lund. Figure 5.3 shows the rainfall-depth distribution observed in Lund during the period from 1978-12-19 to 1979-08-28.

Several researchers have shown that urbanization of the rural areas modifies the precipitation pattern. The increase of annual rainfall totals due to urbanization has been well documented (Huff and Changnon 1966, Changnon 1968, Landsberg 1970). On a short time scale, an increased number of thunderstorms in the built-up areas as compared with rural areas was observed.

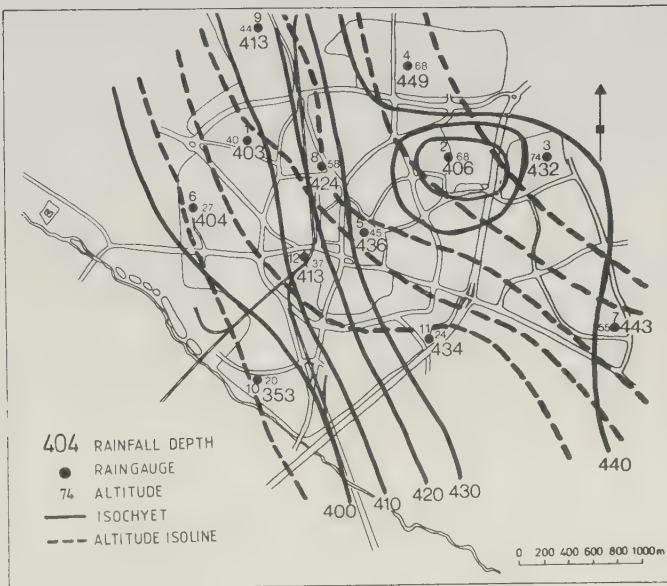


Figure 5.3 Rainfall-depth distribution in Lund during the period from 1978-12-19 to 1979-08-28

These changes are ascribed to greater concentrations of condensation nuclei in the air, increased turbulence, and urban overheating (Kratzer et al 1956, Huff and Changnon 1960, Shaw 1983). Studies in the United Kingdom, however, have failed to relate seasonal rainfall differences to urban development (Tabony 1980). In the London area, for example, rainfall differences are mainly influenced by altitudinal differences (Shaw 1983). Thus, there is no evidence as to whether the local rainfall-depth variation observed in Lund can be explained by the effects of urbanization or by orographic effects. A further analysis of the spatial distribution of the rainfall pattern in Lund with regard to maximum rainfall intensity, made on three years of data, is presented in section 6.4.

The most typical situation when convective rain storms occur in Lund is after the passage of a cold front, especially if the low-pressure area is to the north and the air masses move from the south to the north. Such a situation caused rainfall events No 2, 3, 8 and 9.

The other characteristic situation with regard to the occurrence of convective rainfalls is when no frontal structures are in the area, and a westerly wind brings wet air masses which rise in a convective mechanism and Cumulonimbus clouds occur, resulting in high-intensity rainfalls in Lund. This situation prevailed during rainfall events No 1, 4, 6 and 7.

During rainfall No 5, the convective movement occurred as a result of vertical air-mass transport on the rear of a warm front from the south-east and during winds from the south. Rainfall No 10 was one of the many showers that day in connection with a cold front which passed the Lund area from the south to the north.

To sum up, it can be stated that where Lund is concerned, the most dangerous situation, in terms of high-intensity rainfalls, occurs in connection with cold fronts and southerly winds. Appendix 4 contains synoptic maps presenting the actual meteorological situation for all events described.

5.3 Significance of Rainfall Input for Runoff Simulation

In small urban catchments in southern Sweden, the short summer storms are considered to be the most important ones from the point of view of design and pollution problems. Rainfall durations of some 10-30 minutes with high intensities cause the most serious flooding problems, combined sewer overflows, and result in shock loads of pollutants to receiving waters. Since these high-intensive rains have a very limited spatial extent, it is very important that the areal rainfall input should be chosen for the calibration of the runoff models during these events.

In another project in Lund, the runoff and storm-water quality from five catchments in the city were registered as well as the volume and quality of combined sewer overflows (Hogland and Niemczynowicz 1979, Hogland and Niemczynowicz 1980). Observed extreme rainfall events were used in the calibration of the Storm Water Management Model (SWMM) as well as in the simulation of changes in water-management routines in the city and the assessment of the results of these changes. It has been shown that when only one-point hyetographs are used, serious errors are introduced in the model calibration as well as in the simulation of the runoff (Niemczynowicz and Jönsson 1981b). Figure 5.4 shows an example of SWMM-simulated runoff hydrographs from a three-square-km catchment in Lund; here, different kinds of rainfall input are used.

5.4 Rainfall Intensities for Extreme Events

The absolute maximum 1-minute intensity during the period of two years was 2.31 mm/min observed in one gauge (point value). The same maximum as an areal value for 10 sq.kms. (average of 6 gauges) was 1.37 mm/min.

The maximum 10 minutes' intensity was 1.07 mm/min as a point value and 0.94 mm/min as an areal value. The areal intensities were calculated by means of Thiessen's polygon method, expanding outward from the gauge with maximum point intensity. Table 5.1 lists observed point and areal rainfall intensities for different time periods.

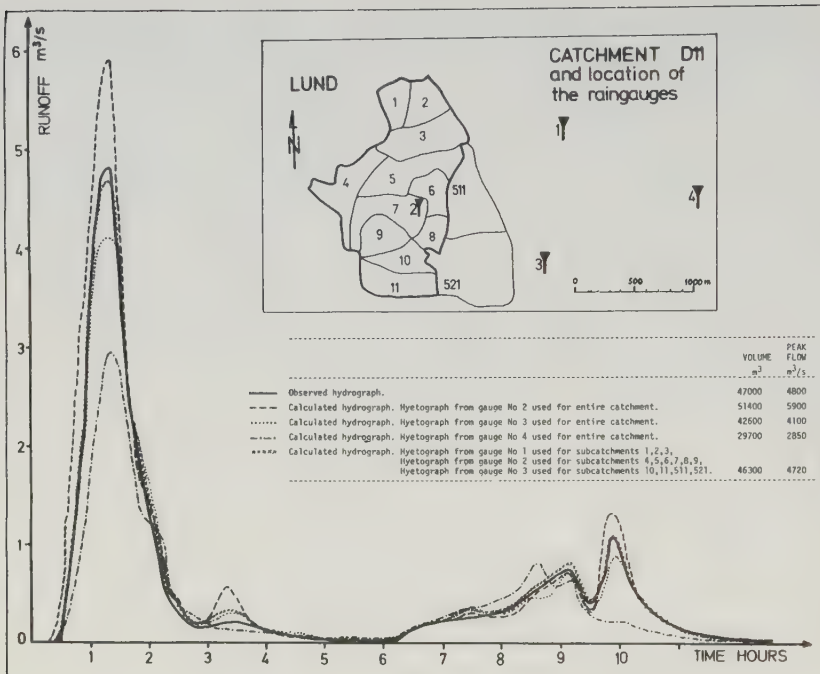


Figure 5.4 SWMM-simulated runoff hydrographs with different kinds of rainfall input

Observed 1-minute rainfall intensities for ten events and for all gauges are listed in Appendix 2. Appendix 3 shows computer-generated hyetograph diagrams for all gauges during all ten rainfall events.

Table 5.1 Maximum rainfall intensities observed during ten extreme events in Lund (mm/min)

1 minutes' duration				10 minutes' duration		
Event	Point	10 km ²	20 km ²	Point	10 km ²	20 km ²
No date	value	value*	value**	value	value*	value**
1 800823	1.59	1.37	0.66	1.07	0.94	0.36
2 800709	2.31	0.60	0.30	1.00	0.56	0.23
3 800713	1.75	0.68	0.48	0.98	0.57	0.34
4 800823	2.25	0.70	0.34	0.95	0.54	0.20
5 790524	1.47	0.58	0.37	0.70	0.40	0.19
6 790921	1.12	0.33	0.18	0.57	0.21	0.16
7 800822	2.11	1.20	0.71	0.57	0.42	0.25
8 800706	1.13	0.55	0.22	0.54	0.39	0.08
9 790625	1.24	0.78	0.51	0.51	0.38	0.15
10 800709	1.10	0.37	0.18	0.49	0.24	0.07

20 minutes' duration

Event	Point	10 km ²	10 km ²
No date	value	value*	value**
1 800823	0.79	0.64	0.37
2 800709	0.63	0.40	0.23
3 800713	0.67	0.47	0.34
4 800823	0.52	0.34	0.20
5 790524	0.43	0.27	0.19
6 790921	0.30	0.16	0.10
7 800822	0.47	0.31	0.25
8 800706	0.38	0.26	0.08
9 790625	0.26	0.20	0.14
10 800709	0.28	0.17	0.07

* - average rainfall intensity from an area with 6 gauges

** - average rainfall intensity from an area with 12 gauges

Figure 5.5 shows the intensity-duration curves for ten events with point values, 10 sq.kms. values and 20 sq.kms. values. For comparison, the synthetic intensity-duration curves with a return period of 0.5, 1, 2, 5 and 10 years are included in the point value diagram. There are no original i-d-f curves available for the region of Lund. The curves shown were calculated using a "Z" factor (Dahlström 1978), which makes such calculations possible for any point in Sweden.

Table 5.1 and Figure 5.5 show that all rainfall intensities decline with increasing duration and area. It can be noticed that high-intensity rainfalls were rather well represented during two years of observations, as the curves for 4 out of 10 observed events are situated above a 2-year return period curve. Event No 1 has a return period of somewhere between 5 and 10 years. From the diagram, Figure 5.5, it can also be seen that the intensity-duration curves for observed events do not follow the synthetic curves smoothly with any return period.

For example, event No 1 has a return period of about 7 years when it is regarded as a 10-minute average value, but only a 4-year return period when the average value is for 30 minutes. It can also be noted that rainfall volumes observed during this type of storm definitely depend on the size of the area.

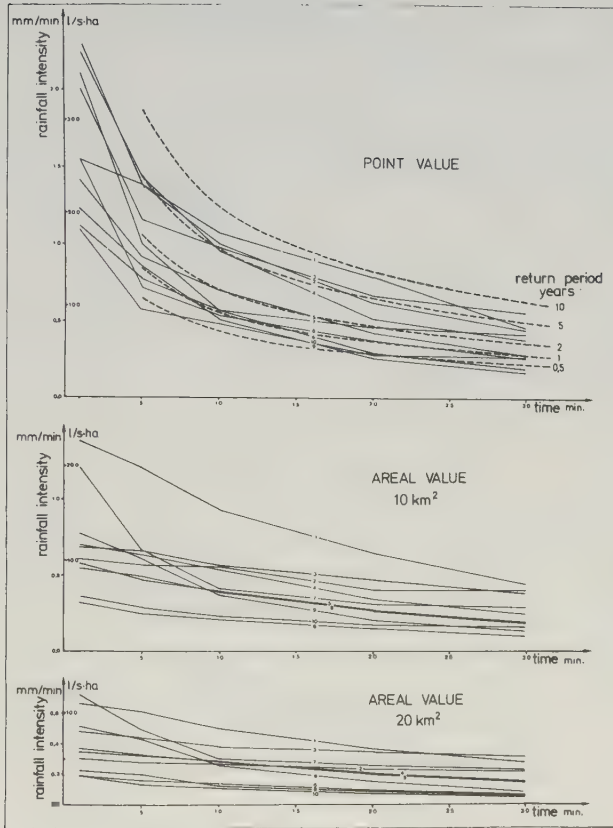


Figure 5.5 Intensity-duration curves for 10 extreme rainfall events in Lund (solid lines). I-d-f curves calculated with Z-factor (Dahlström 1979) are shown as dotted lines on the point-value diagram

5.5 Storm-Centered Area Reduction Factors

In order to show how the areal rainfall intensity decreases with an increasing area, the storm-centered area reduction factors (ARF-s) have been calculated. Calculations were made for individual rainfall events.

ARF-s represent the ratio between the maximum areal rainfall within the storm zone for the given area and duration, and the maximum point rainfall within the same storm zone and the same duration (Bell 1976). For each event, calculations started from the area represented by the gauge with the highest rainfall intensity (storm-centered ARF-s). The areas represented by individual gauges were determined by the Thiessen polygon method. Figure 5.6 shows ARF-s calculated for all 10 rainfall events and different time periods.

Storm-centered ARF-s are, quite simply, descriptions of the rainfall properties of the individual storms. They tell us nothing about the rainfall frequency distribution for a given area. Such a description cannot be generalized and made to cover other storms as well, since the area with the highest rainfall intensity varies from event to event and the location of this area cannot be predicted. As can be seen from Figure 5.6, ARF-s decline differently in respect to different events.

The fixed area ARF-s have been recognized as being more useful for practical applications, being more statistical in character, as they represent the ratio between areal and point rainfall with the same return period (Bell 1976, Rodriguez-Iturbe and Meija 1974b). The possession of statistically calculated fixed area ARF-s would make it possible to construct

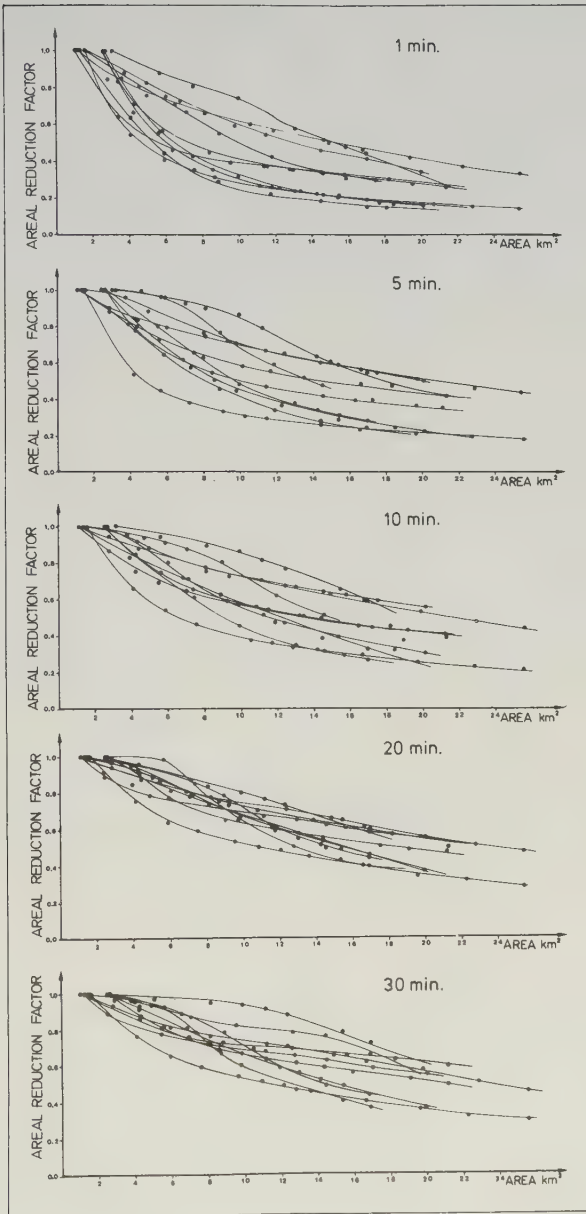


Figure 5.6 Areal reduction factors for 10 extreme rainfall events in Lund

the areal i-d-f curves from one-point i-d-f curves. Or the opposite: having one-point i-d-f curves and the fixed area ARF-s would ensure that areal i-d-f curves could be calculated. (For further studies, see chapter 7). 24-hour fixed area ARF-s have been derived from 14 years' data on 9 areas of 1000 sq.km. in the United Kingdom, and from 10 to 15 years' data on an area of 3000 sq.km. in the United States (Bell 1976, Rodriguez-Iturbe and Meija 1974b). From an urban-hydrological point of view, it would be interesting to derive fixed area ARF-s for much shorter rainfall durations and smaller area sizes.

5.6 Size, Shape and Movement of the Raincells

In order to describe the characteristics of the raincell, some arbitrary definitions have to be made. Since the limits of the raincell are not sharply defined, an arbitrary borderline of the raincell has to be established. On the other hand, in order to make a comparison between the different rainfall cells possible, the extension of the raincells for different events must be selected in the same way.

If the network of gauges is sufficiently dense, it is reasonable to expect that more than one gauge will observe the same raincell. It is also reasonable to expect a high correlation between hyetographs observed by the gauges within the same raincell.

An estimation of the drift of storm across the network was made by means of a correlation analysis technique (Marshall 1980). One-minute isohyetal plots (not shown here) indicate that the rainfall pattern at adjacent gauges is often similar, but there is a time lag from one gauge to the next one. The apparent consistency of these lags suggests that they represent the drift of the rainstorm over the area covered by the gauge network.

A procedure for estimating the velocity and direction of the drift of the raincells was incorporated into a computer program. The procedure is based on the sample crosscorrelation between all possible combinations of gauges. The measure of

the association between gauges i and j for time lag τ is a sample cross-correlation $R_{i,j,\tau}$:

$$R_{i,j,\tau} = \frac{\sum_{t=1}^{T-\tau} (x_{i,t} - \bar{x}_i) (x_{j,t+\tau} - \bar{x}_j)}{\left(\sum_{t=1}^T (x_{i,t} - \bar{x}_i)^2 \right)^{1/2} \left(\sum_{t=1}^T (x_{j,t} - \bar{x}_j)^2 \right)^{1/2}}$$

where

$x_{i,t}$ is the rainfall intensity at gauge i and time t ,

$x_{j,t}$ is the rainfall intensity at gauge j and time t ,

$$\bar{x}_i = \frac{1}{T} \sum_{t=1}^T x_{i,t}$$

$$\bar{x}_j = \frac{1}{T} \sum_{t=1}^T x_{j,t}$$

T is the rainfall duration

Let (u_i, v_i) and (u_j, v_j) represent the coordinates of gauges i and j ; the relative coordinates of i and j are then defined as:

$$u_{i,j} = u_i - u_j \quad \text{and} \quad v_{i,j} = v_i - v_j$$

Under the assumption of spatial stationarity, the lag- τ cross-correlation between i and j is considered to be only a function of τ , $u_{i,j}$ and $v_{i,j}$. Thus the cross-correlations do not depend on the absolute positions of gauges i and j , but only on their relative positions. In the relative coordinate systems (U, V) a lag- τ correlation surface can be envisaged. Each pair of gauges produces two points on a (U, V) plane, representing values of $R_{i,j,\tau}$ and $R_{j,i,\tau}$ placed in a positions $(U_{i,j}, V_{i,j})$ and $(-U_{i,j}, -V_{i,j})$. Thus the $n(n-1)/2$ pairs of gauges provide $n(n-1)$ points, where n is the number of gauges in service.

Figure 5.7 shows lag zero correlations for event No 7. The nonexistence of a value due to missing data is shown by a dot and cross-correlations are omitted from the figure. In the same way correlation diagrams were produced for time lag between the hyetographs, increasing by a one-minute time step. Finally, the iso-correlation lines were drawn on each correlation diagram.

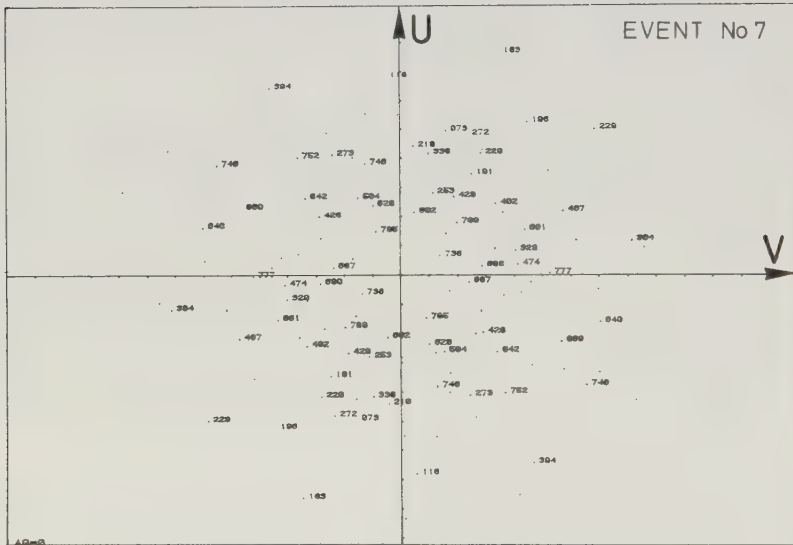


Figure 5.7 The lag zero correlation for event No 7

Figure 5.8 shows the example of a correlation diagram with isolines drawn for correlation coefficients 0.5, 0.6 and 0.7. The "COLOR" system was used for contour map plotting (Jern 1980).

In order to produce correlation values in a regular gridnet and to smooth out the errors, a moving-averages procedure in two dimensions was applied. Values within a circle with a radius of 500 m were averaged with equal weight, and the result was assigned to the centre of the circle. Then the circle was moved in steps of 500 m, and the procedure was repeated until the grid was filled. NORMAP library routines were used to produce isoritmnic maps (Nordbeck 1973).

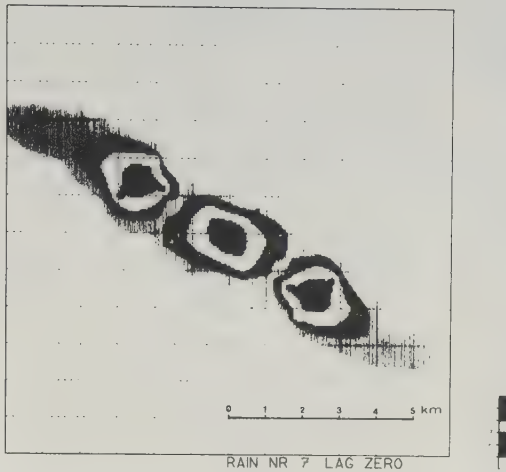


Figure 5.8 An example of a correlation diagram

In the manner described above, a number of graphs were obtained where the areas limited by a 0.7 correlation isoline moved in the direction of the rainfall movement. The speed and the direction of raincell movement were then calculated by following the movement of the centre of gravity of the area limited by a 0.7 correlation isoline.

Figure 5.9 contains a diagram of correlation coefficients for all ten extreme rainfall events. The isolines shown represent correlations with a zero time lag. The movement of raincells is indicated by a thick line drawn through the centers of gravity of the figures, limited by 0.7 correlation isolines drawn with consecutively increasing time lag.

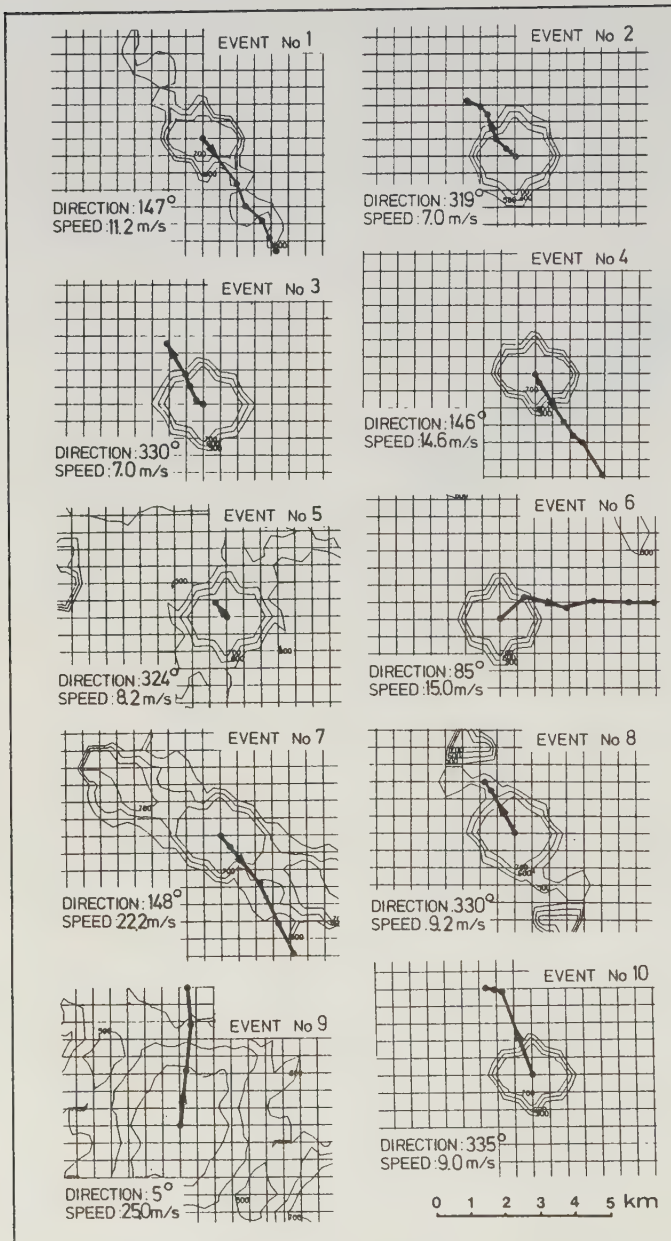


Figure 5.9 Correlation diagrams showing the shape, size and movement of the raincells

Table 5.2 lists the speed, size and direction of movement of the rainfall cells for ten extreme rainfall events.

Table 5.2 Size, speed and direction of movement of the rainfall cells during ten extreme events

Event No	R a i n f a l l c e l l			Wind direction	
	Speed m/s	Direction (clockwise from N) Degree	Size km ²	Observed at Sturup air- port	Observed in Copenhagen Degree
1	11.2	147	2.0	SE	155
2	7.0	319	2.9	WNW	123
3	7.0	330	3.0	NNE	60
4	14.6	146	2.3	SE	155
5	8.2	324	2.8	WSW	355
6	15.0	85	2.3	ENE	70
7	22.2	148	3.6	E	125
8	9.2	330	2.8	NNE	3
9	25.0	5	7.6	ENE	5
10	9.0	335	2.2	WNW	303

The wind directions shown in Table 5.2 were observed on the ground level at the airport in Sturup, about 18 kms to the south-east, and at Kastrup airport in Copenhagen, about 20 kms to the west of Lund.

Table 5.2 shows that there is - with some exceptions - a good agreement between the calculated storm movement direction and the direction of wind observed on the ground level.

5.7 Conclusions

Serious errors in hydrograph simulation can be introduced, if the one-point rainfall input is used instead of an areal rainfall input. If the historical single events are to be used in runoff model calibration or in runoff simulations, knowledge of areal rainfall patterns and rainfall volume is essential.

A true spatial distribution of rainfall is never really known for sure; nor is a true rainfall volume. Using a number of one-point hyetographs from a number of gauges assigned to different parts of the catchment will increase the accuracy of areal rainfall estimation. Observations in Lund suggest that a reasonable density of gauges for practical purposes is one gauge per 2 or 3 sq kms.

Storm-centered Areal Reduction Factors derived in Lund confirm the conclusion that the areal intensities of short-term rainfalls decrease with the increasing size of the area. These ARF-s, however, cannot be used for the areal reduction of point intensity-duration-frequency curves, since they do not supply the rainfall-frequency distribution for any given area. In order to be able to calculate areal i-d-f curves, the area-centered ARF-s, based on the time series of observations in a dense network of gauges, must be derived. Such areal i-d-f curves, based on areal rainfall statistics, could be used in choosing "design storms".

The size of the raincells observed in Lund during ten extreme rainfall events, defined as an area within a 0.7 correlation isoline, varies between 2.0 and 7.6 sq.kms. The speed of the raincells observed in Lund varies between 7.0 and 25.0 m/s. The direction of raincell movement is generally in good agreement with the wind direction observed at the ground level.

The most intense convective rainfall events occur in Lund in connection with the passage of cold fronts and winds from the south.

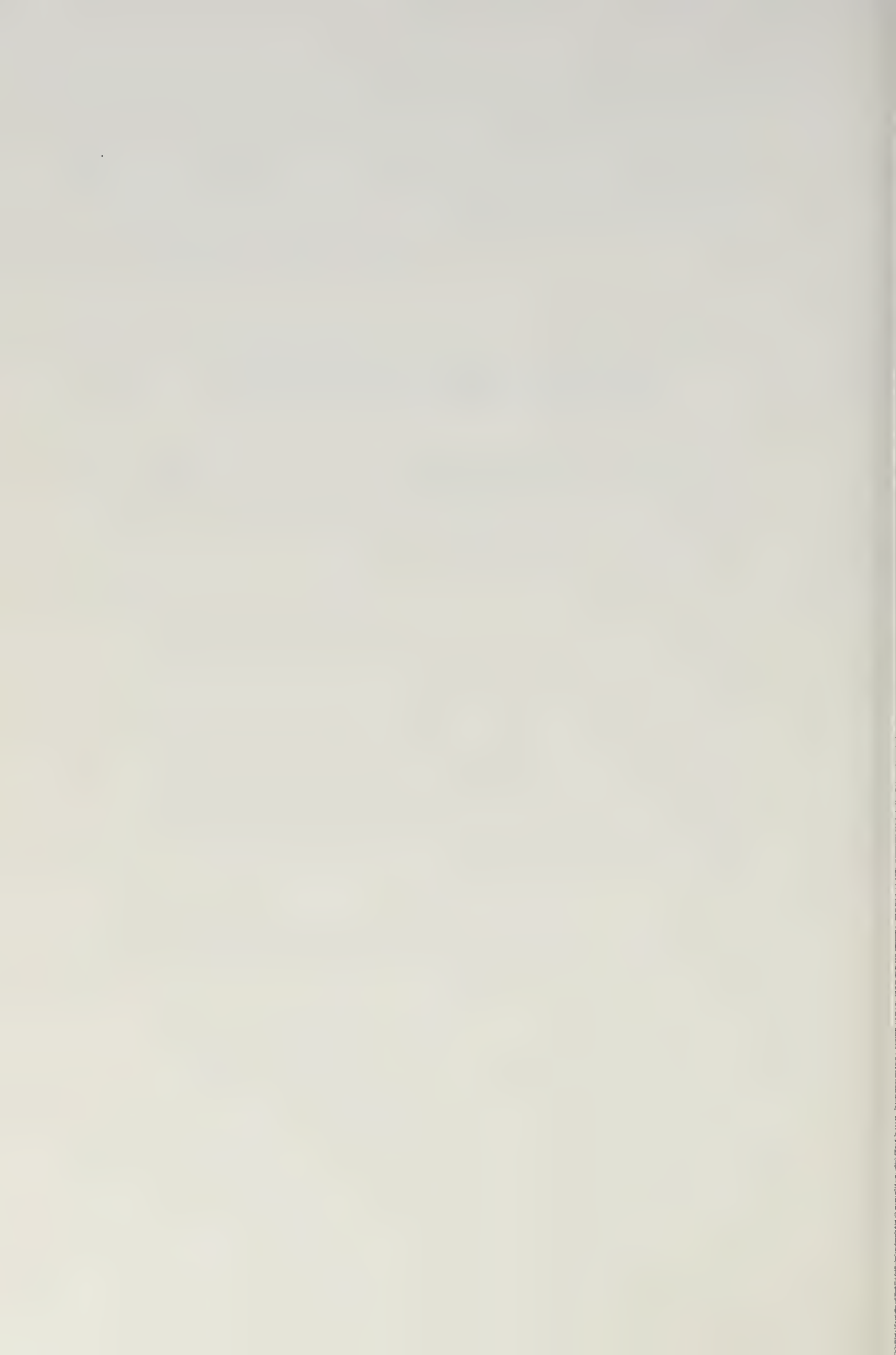
6. AREAL INTENSITY-DURATION-FREQUENCY CURVES AND STATISTICAL AREAL REDUCTION FACTORS

This chapter presents a new method of areal rainfall analysis, developed by the author. The areal intensity-duration-frequency curves and the statistical areal reduction factors which were derived with the aid of this new method can be used in practical applications. This chapter is, to a major extent, based on the following publications:

Niemczynowicz, J (1982): "Areal Intensity-Duration-Frequency Curves and Areal Reduction Factors for Short-term Rainfall Events in Lund". Department of Water Resources Engineering, Lund Institute of Technology, University of Lund, Report No 3065.

Niemczynowicz, J (1982): "Areal Intensity-Duration-Frequency curves for Short-Term Rainfall Events in Lund". Nordic Hydrology, 4 (193-204).

Niemczynowicz, J (1983): "Areal Intensity-Duration-Frequency Curves - a Possible Way of Improving the Rainfall Input". Proceedings of the SWMM-user's Group Meeting, Gainesville, Florida, USA (pp 192-201).



6. AREAL INTENSITY-DURATION-FREQUENCY CURVES AND STATISTICAL AREAL REDUCTION FACTORS FOR SHORT-TERM RAINFALL EVENTS IN LUND

6.1 Introduction

Intensity-duration-frequency (i-d-f) relationships, usually derived from point rainfall measurements, have long been used in synthesizing so-called "design storms". Simple block rain can easily be derived from i-d-f curves for the desired duration and return period and then be put to use in the simulation of runoff.

As long as the rational method was used, no proof could be found that statistical information taken from point i-d-f curves was not always sufficient for design purposes. Later on, when more sophisticated methods of runoff prediction came into common use, it was realized that the single block rain not only gives the wrong picture of a hyetograph, but also yields the wrong rainfall volume. (Arnell 1982).

Convective storms, which are particularly significant for design purposes, are rather limited in space. Design storms derived from point i-d-f curves have no areal dimensions, but are nevertheless used for runoff simulations on catchments of different sizes. We can reduce this idea "ad absurdum" by trying to imagine one single design storm falling simultaneously on thousands of square kilometers. It is obvious that reducing factors of some kind which takes the areal properties of a rainfall into consideration have to be used, especially when modeling runoff from large catchments. Areal Reduction Factors (ARF-s) have been developed and used in many countries for a long time (U.S. Weather Bureau 1958, Bell 1976, Rodriguez-Iturbi and Meija 1974b, Nguyen and Rouselle 1981).

Most of these relationships denote a far more extensive time and space scale than is relevant for practical urban hydrology applications, such as the design and analysis of urban storm systems. The scale which is of interest in this context ranges in time from 1 minute to some 30-40 minutes and in space from 1 to about 30-50 sq.kms.

With regard to i-d-f curves, statistical information is comprehensive and convenient. It is therefore reasonable to expect that design storms will still be used for some time. One possible way of improving the rainfall input derived from i-d-f curves is to develop AREAL INTENSITY-DURATION-FREQUENCY curves valid for the time and space scale relevant in urban hydrology. Another way is to develop area-rainfall depth relationships from which factors reducing rainfall from point to areal values can be obtained for different areas, durations and return periods. Those factors can then be used to reduce the design storms from point to areal values. These solutions are more practical than complete, because neither areal i-d-f curves nor areal reduction factors describe the dynamics of moving storms.

The third, and the most desirable, solution is to develop a statistical model simulating a rainfall series, a model which gives due consideration to temporal, spatial and dynamical variations in the rainfall pattern (Bras and Rodriguez-Iturbi 1976, Amorocho and Wu 1977, Gupta and Waymyre 1979).

The need for reasonable rainfall-input for runoff simulations in big cities has led to a number of area-rainfall depth relationships being developed in different countries (Abraham et al 1976, Bell 1976, Rodrigues-Iturbi et al 1974, Nguyen 1983, Lindholm 1983). One vital problem which cannot be ignored is the lack of sufficiently long time series of observations on a dense network with good time synchronization.

The raingauge network installed in Lund in 1978 covers, approximately, an area of 25 square kilometers, and it has 12 gauges. More than three years of registered data are assumed to be sufficient for producing reasonably good statistics where short-term rainfalls are concerned.

This paper describes point and areal i-d-f curves derived for the city of Lund. The areal relationships presented here will provide more realistic design storms in comparison with design storms derived from point relationships. The question of the validity of the presented relationships outside the city of Lund is beyond the scope of this work.

6.2 The Data Base

The rainfall series from all twelve gauges were divided into rainfall events with an arbitrarily chosen, 40-minute interval between the events. Since the main goal of this study is to compare the point rainfall statistics with the areal rainfall statistics for short-term rainfalls, all events with low intensity were removed from the data base. The criterion chosen was that all events with a rainfall depth of less than 0.35 mm observed during ten successive minutes were excluded from the data base. If any one of the gauges exceeded the criterion, data from all other gauges were accepted for the same period of time. It was found that this procedure only eliminated rainfall events with a very uniform temporal and spatial distribution. All data suspected of being wrong, and all events with less than eight gauges in operation, were taken away from the data base. This data base, originally consisting of about 130 thousands lines, was reduced to 20 thousand lines. A total of 588 rainfall events were finally included in the data base.

Malfunction of the gauges was observed or suspected about 15 % of the time, on the average. Gauge No 1 was the worst, malfunction occurring during 38 % of the time; gauges No 2, 3 and 8 were functioning all the time. Most of the malfunctions were caused by broken telephone lines.

6.3 Point Intensity-Duration-Frequency Relationships

Point i-d-f curves were developed separately for all 12 gauges in Lund. The one hundred maximum values of rainfall intensity were found for the durations of 1, 5, 10, 15, 20, 30 and 40 minutes. The intensities for each duration were then ranked and listed for each gauge. The return period pertaining to each intensity and duration was calculated by dividing the total time during which the gauge was working by the rank number. Descending maximum intensities were then plotted on a linear scale against the return periods for each duration and gauge.

A smoothed-out curve can be drawn manually, or by fitting some mathematical distribution function. Several investigators have found that the Log-Pearson Type III distribution function fits well with the maximum rainfall intensity data (Arnell 1982). Since our main concern is the differences between point and areal rainfall, no other distribution functions were tested during this study.

A Log-Pearson distribution function was fitted to the observation points by means of the method of moments, according to a computer program provided by Kite (Kite 1977).

Figure 6.1 shows an example of the intensity-return period diagram, with observed values and fitted distribution function, for one of the gauges. Values from the fitted distribution curves were then rearranged, and the intensity-duration-frequency curves, in their usual form, were drawn as shown in Figure 6.2. The described procedure was followed with regard to all 12 gauges and resulted in 12 complete i-d-f curves, each of them representing a point value. The mean point-value i-d-f curve was finally calculated by means of averaging

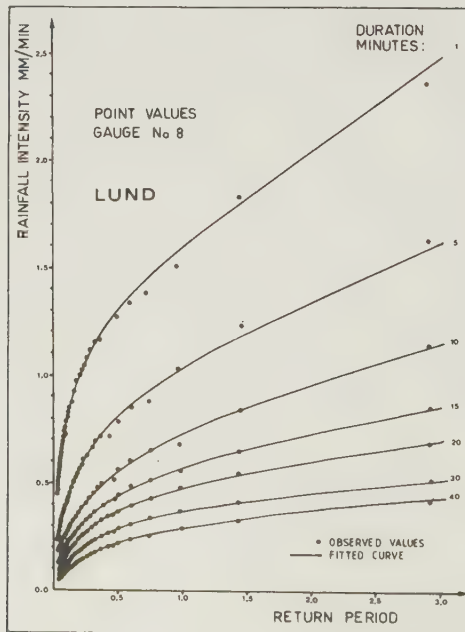


Figure 6.1 Intensity-return period diagram for gauge No 8

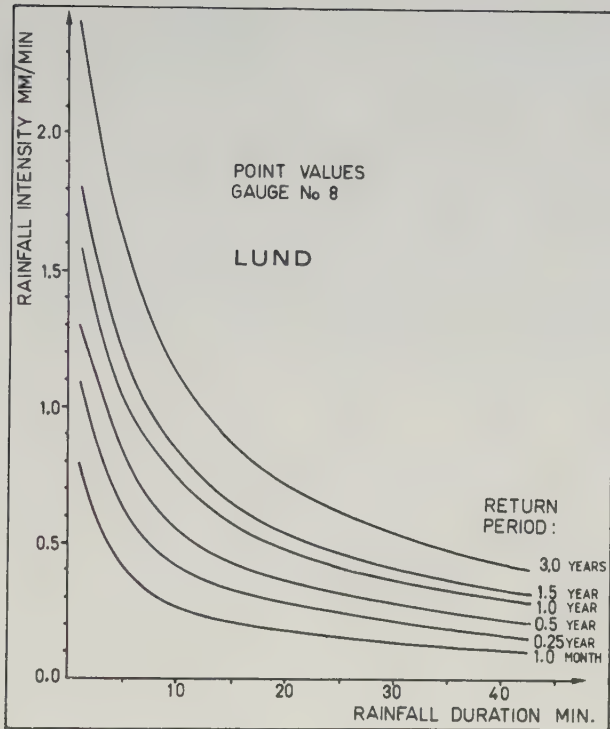


Figure 6.2 Intensity-duration-frequency curves for gauge No 8

the values for all durations and return periods. Figures 6.4 - 6.7 contain the point and areal mean-value i-d-f curves. The values of maximum average intensities for different durations and return periods, estimated by the Log-Pearson Type III distribution function, are shown in Table 6.4.

6.4 Spatial Variations of Rainfall Intensity

Due to the cellular structure of the rainfall pattern, and to the nonuniform distribution of rainfall cells in space, each individual raingauge registers a different rainfall hyetograph during the same rainfall event. Moreover, each individual gauge has its own inaccuracies due to internal (instrumental) and external (situation, altitude etc) reasons. Time pattern, total volume, and maximum rainfall intensity are not the same in different gauges. Also intensity-duration-frequency curves derived from the data collected by different raingauges are different.

Table 6.1 gives the range of differences in maximum intensities observed between 12 gauges in Lund. The highest (Max), the lowest (Min), the mean values (Mean), the standard deviations between 12 gauges (s), and the coefficients of variation ($CV = s/\text{mean}$) pertaining to different durations and return periods are stated. The differences between the highest and the lowest values and standard deviations decrease quickly where shorter return periods are concerned. The coefficient of variation seems to be fairly constant for all durations within the same return period; but it decreases as the return period becomes shorter. Obviously, extreme intensity values are the ones that are most unevenly distributed in space. The highest values of intensity occur persistently in gauges No 2, 3, 4, 5 and 12, which are situated in the central part of the town, and with a downwind direction, i.e. to the north-east from the city center. The lowest intensity values are typical of gauges No 9, 1, 11 and 6, situated outside the town.

The spatial variation of the maximum rainfall intensity over the city of Lund, expressed as percentual deviations from the 12-gauge average, is demonstrated in Figure 6.3. Shown deviations are the average values from rainfall durations of 1, 5 and 10 minutes; they were derived from rainfall intensities representing a 3-year return period (Figure 6.3a), a 1.5-year return period (Figure 6.3b), a 1-year return

Table 6.1 Maximum rainfall intensities observed in 12 gauges in Lund during a three years period. (The number of the gauge where the value was observed is in parenthesis).

MAXIMUM INTENSITY MM/MIN	D U R A T I O N I N M I N U T E S						
	1	5	10	15	20	30	40
RETURN PERIOD 3.0 YEARS							
Max	3.19(7)	1.98(2)	1.36(3)	1.00(2)	0.84(3)	0.62(3)	0.55(4)
Min	1.31(9)	1.08(11)	0.86(9)	0.64(9)	0.51(9)	0.40(9)	0.37(9)
Mean							
12 gauges	2.20	1.61	1.20	0.93	0.76	0.57	0.47
s	0.61	0.51	0.43	0.34	0.26	0.18	0.15
CV	0.27	0.24	0.26	0.32	0.37	0.41	0.37
RETURN PERIOD 1.5 YEAR							
Max	2.03(6)	1.50(12)	1.15(12)	0.93(12)	0.74(5)	0.51(7)	0.44(2)
Min	1.27(9)	0.93(11)	0.68(9)	0.52(9)	0.48(9)	0.35(9)	0.28(9)
Mean							
12 gauges	1.71	1.26	0.96	0.75	0.60	0.44	0.36
s	0.23	0.18	0.14	0.11	0.07	0.05	0.05
CV	0.13	0.14	0.15	0.14	0.12	0.11	0.13
RETURN PERIOD 1.0 YEAR							
Max	1.88(12)	1.32(12)	0.92(12)	0.66(5)	0.53(7)	0.42(5)	0.38(5)
Min	1.24(9)	0.75(6)	0.59(9)	0.50(9)	0.40(9)	0.31(6)	.28(11)
Mean							
12 gauges	1.51	0.98	0.76	0.60	0.48	0.35	0.30
s	0.23	0.19	0.09	0.05	0.04	0.04	0.03
CV	0.15	0.19	0.12	0.08	0.08	0.11	0.10
RETURN PERIOD 0.5 YEAR							
Max	1.45(5)	0.78(7)	0.61(12)	0.49(3)	0.39(8)	0.31(1)	0.26(1)
Min	0.87(4)	0.60(4)	0.42(6)	0.36(4)	0.31(4)	0.23(4)	0.18(4)
Mean							
12 gauges	1.16	0.71	0.51	0.42	0.36	0.28	0.22
s	0.13	0.06	0.06	0.04	0.02	0.03	0.02
CV	0.12	0.08	0.11	0.09	0.06	0.09	0.10
RETURN PERIOD 0.25 YEAR							
Max	1.09(8)	0.68(8)	0.43(9)	0.33(2)	0.30(11)	0.21(7)	0.18(8)
Min	0.77(1)	0.44(4)	0.35(6)	0.27(6)	0.22(10)	0.18(6)	0.15(6)
Mean							
12 gauges	0.89	0.56	0.39	0.30	0.25	0.20	0.17
s	0.10	0.06	0.03	0.02	0.02	0.01	0.01
CV	0.12	0.10	0.06	0.08	0.09	0.06	0.05
RETURN PERIOD 1.0 MONTH							
Max	0.57(8)	0.34(8)	0.24(8)	0.20(8)	0.17(8)	0.13(8)	0.11(8)
Min	0.45(4)	0.24(10)	0.19(10)	0.15(10)	0.13(10)	0.11(7)	0.09(6)
Mean							
12 gauges	0.49	0.29	0.20	0.17	0.15	0.12	0.10
s	0.03	0.03	0.03	0.01	0.01	0.01	0.01
CV	0.07	0.09	0.15	0.08	0.08	0.06	0.05

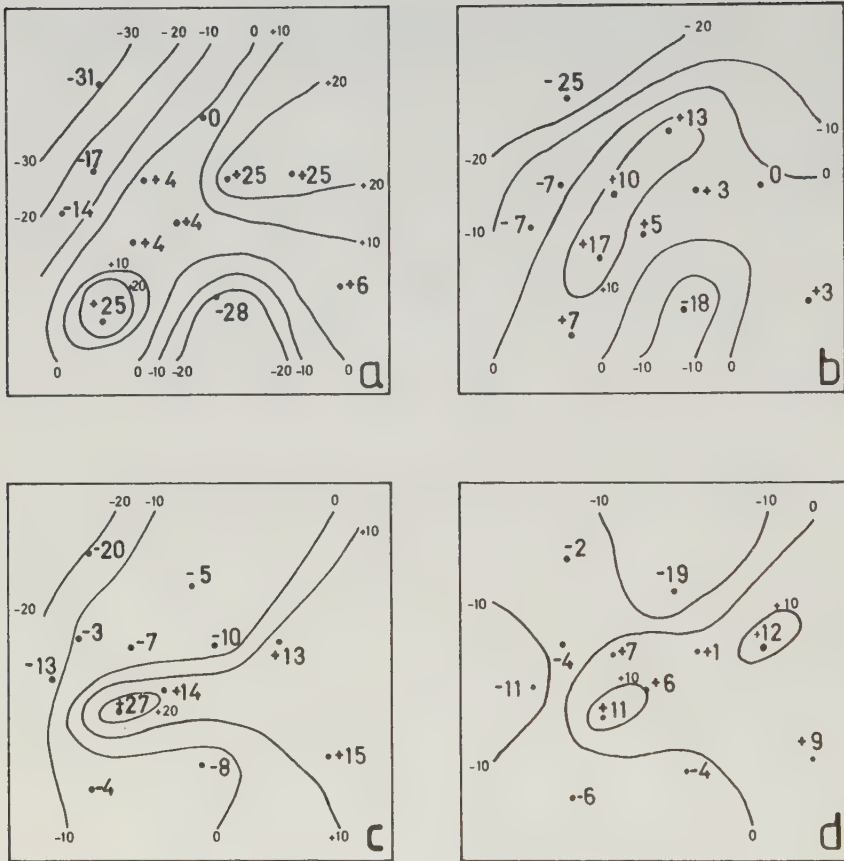


Figure 6.3 Percentual deviations of rainfall intensity observed in individual gauges from the average 12-gauge rainfall intensity

- a - 3-year return period
- b - 1,5-year return period
- c - 1-year return period
- d - 0,5-year return period

period (Figure 6.3c), and an 0.5-year return period (Figure 6.3d). Figure 6.3 shows that the rainfall intensities of different return periods generally increase with the west-to-east wind direction, which is the prevalent one.

From Figure 6.3, it can also be noted that the highest deviations from the average rainfall intensity are observed during rainfalls with long return periods, i.e. during the most intensive rainstorms.

A strong local variation with regard to rainfall depth in Lund, which can probably be explained as an orographic effect, has been observed previously (see Section 5.2 and Niemczynowicz and Jönsson 1981b). The rainfall sums from individual gauges were also derived from the data base used for deriving areal i-d-f curves, which only contains intensive rainfalls. A comparison of these rainfall sums, is supplied in Table 6.2, it does not provide a clear picture of local variation.

Table 6.2 Rainfall sums of 12 gauges in Lund for the period 781224-811125.

Raingauge No	Rainfall Sum (mm)	Raingauge No	Rainfall Sum (mm)
1	1113	7	1143
2	1205	8	1253
3	1146	9	1077
4	1172	10	1125
5	1145	11	1134
6	1113	12	1144

The orographic effect was found by means of analyzing a complete time series of a rainfall, and the data base used for deriving i-d-f curves includes only short-term, high intensity rainstorms. It can be indirectly concluded that most of the altitude differences in rainfall sums are created during long and low-intensive rainfall events.

6.5 Areal Intensity-Duration-Frequency Relationships

In order to extrapolate rainfall data from point measurements to areal values, specific areas were connected with all gauges. The influence that different methods of extrapolating point values to areal averages have on the accuracy

of areal estimation was investigated by Gottschalk and Jutman (1982). The results show that the magnitude of error is, to a minor extent, influenced by the method of extrapolation. The method of Thiessen polygons was chosen for this study, as it simplifies calculations. Table 6.3 lists the areas which the 12 gauges represented according to Thiessen polygons.

Due to periodic malfunction, the gauges represented slightly different areas during the same periods of observation. In order to develop areal relationships, mean rainfall values

Table 6.3 Areas connected with raingauges in Lund

Gauge No	Area Sq.km.	Gauge No	Area Sq.km.	Gauge No	Area Sq.km
1	1.56	5	1.48	9	1.65
2	1.82	6	2.11	10	2.80
3	2.92	7	2.57	11	2.91
4	2.52	8	1.44	12	1.56

from a number of gauges had to be treated simultaneously. In order to avoid reducing the total length of the record by averaging the observation period for all gauges, a special routine for reproducing the missing values was developed.

The average weighted values from the three nearest functioning gauges were inserted in place of the missing values for each minute of the data base. After this procedure, a new point i-d-f relationship was developed for all 12 gauges. No significant changes in results were observed after this procedure.

All further calculations were performed on the same data base with reproduced missing values.

Areal i-d-f curves were developed by means of performing calculations (described in Section 6.3) on mean weighted values from combinations of the gauges. Each combination consists of 12 groups of gauges. In each combination, the same gauge is represented the same number of times.

For example, a mean-value i-d-f curve representing an area of two gauges was developed as follows: the mean value of rainfall intensity pertaining to each minute in the data base was calculated for the arbitrarily chosen group of two gauges. Intensity-duration-frequency relationships were then developed for this group. The next two-gauge group was chosen, and new relationships were developed. Calculations proceeded until 12 groups of gauges had been treated. This resulted in 12 different, complete intensity-duration-frequency relationships representing different areas of gauge pairs. Finally, the man-value relationship was calculated, representing the mean area of 12 gauge pairs.

The same calculating procedure was carried out for the groups consisting of 3, 4, 5, 6, 8, 10 and 12 gauges. Intensity-duration-frequency curves for the point value, and the 4, 10 and 25 sq.km values, are presented in Figures 6.4 - 6.7.

The point and areal mean values of the maximum intensity for different durations and return periods, fitted to the log-Pearson Type III distribution function, are shown in Table 6.4.

All intensity-duration-frequency curves were fitted to a mathematical expression of the form:

$$I = \frac{a}{T + b} + c$$

where

- I - maximum areal rainfall intensity for duration T (mm/min)
 T - rainfall duration (min)
 a,b,c - constants

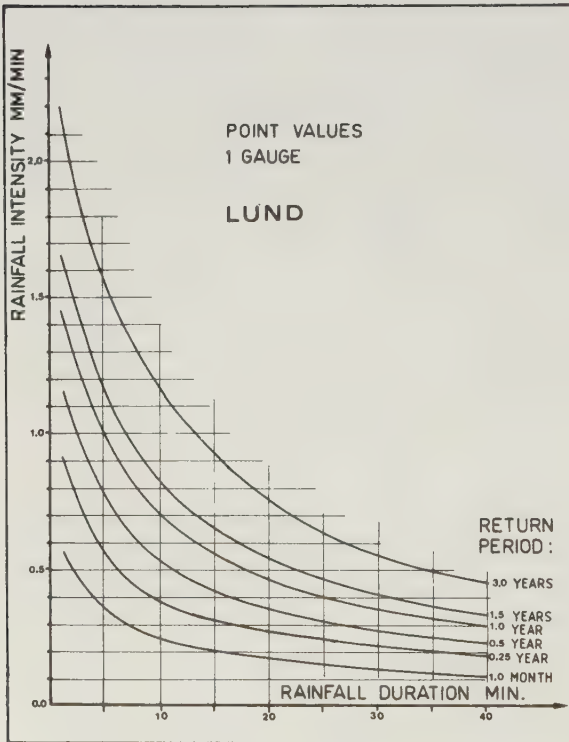


Figure 6.4 Point intensity-duration-frequency curves for the city of Lund

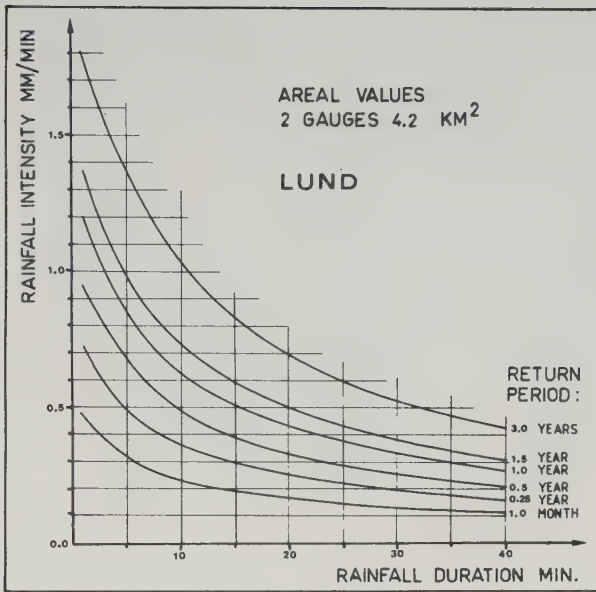


Figure 6.5 Areal intensity-duration-frequency curves for the city of Lund. Area 4.2 sq.kms.

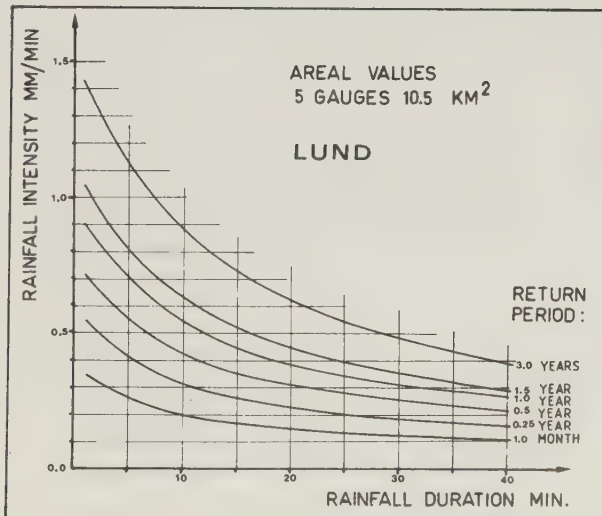


Figure 6.6 Areal intensity-duration-frequency curves for the city of Lund. Area 10.5 sq.kms.

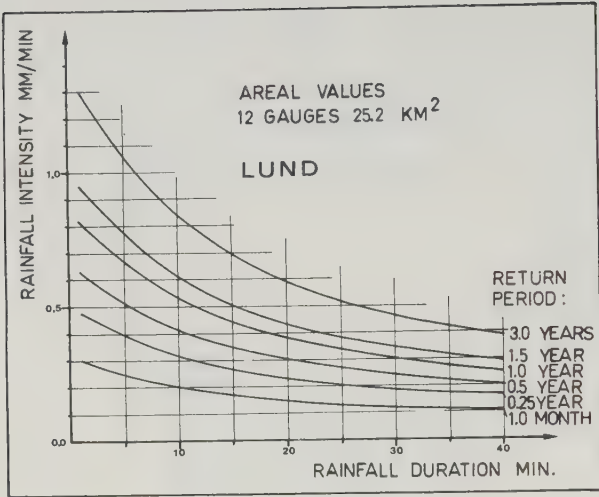


Figure 6.7 Areal intensity-duration-frequency curves for the city of Lund. Area 25.2 sq.kms.

The constants a , b and c were calculated using the least squares criterion and the optimization routine according to Marquardt's method. (Ericsson 1979). The constants a , b and c for the point and areal values are given in Table 6.5.

It transpires from the presented point and areal intensity-duration-frequency relationships that the return period of a given point rainfall has to be increased by about 50% for a catchment size of 25 sq.kms. and for durations up to 30

Table 6.4 Point and areal mean-values of the maximum rain-fall intensity for different durations and return periods fitted to observation points by Log-Pearson typ III distribution function.
(mm/min)

RETURN PERIOD	D U R A T I O N I N M I N U T E S						
	1	5	10	15	20	30	40
POINT VALUE (AREA 2.1 SQ KM 1 GAUGE)							
3.0 YEARS	2.19	1.55	1.17	0.92	0.74	0.55	0.45
1.5 YEAR	1.64	1.11	0.82	0.64	0.53	0.40	0.32
1.0 YEAR	1.44	0.96	0.70	0.55	0.45	0.34	0.28
0.5 YEAR	1.14	0.74	0.53	0.42	0.35	0.27	0.22
0.25 YEAR	0.89	0.53	0.39	0.31	0.26	0.22	0.17
1.0 MONTH	0.56	0.33	0.24	0.19	0.16	0.13	0.11
AREAL VALUE (AREA 4.2 SQ KM 2 GAUGES)							
3.0 YEARS	1.80	1.35	1.04	0.83	0.68	0.52	0.42
1.5 YEAR	1.35	0.98	0.74	0.59	0.49	0.37	0.31
1.0 YEAR	1.18	0.85	0.63	0.51	0.42	0.32	0.27
0.5 YEAR	0.94	0.65	0.48	0.39	0.33	0.25	0.21
0.25 YEAR	0.72	0.48	0.36	0.30	0.24	0.20	0.16
1.0 MONTH	0.46	0.30	0.22	0.18	0.16	0.13	0.11
AREAL VALUE (AREA 6.3 SQ KM 3 GAUGES)							
3.0 YEARS	1.67	1.29	1.00	0.80	0.66	0.51	0.41
1.5 YEAR	1.22	0.92	0.70	0.57	0.47	0.37	0.30
1.0 YEAR	1.06	0.79	0.60	0.49	0.41	0.32	0.26
0.5 YEAR	0.83	0.61	0.46	0.38	0.32	0.25	0.21
0.25 YEAR	0.64	0.42	0.35	0.30	0.24	0.20	0.15
1.0 MONTH	0.41	0.28	0.21	0.18	0.15	0.12	0.10
AREAL VALUE (AREA 8.4 SQ KM 4 GAUGES)							
3.0 YEARS	1.53	1.22	0.97	0.77	0.64	0.49	0.40
1.5 YEAR	1.12	0.87	0.68	0.55	0.46	0.36	0.29
1.0 YEAR	0.98	0.75	0.58	0.48	0.40	0.31	0.26
0.5 YEAR	0.77	0.58	0.44	0.37	0.31	0.24	0.20
0.25 YEAR	0.57	0.42	0.33	0.27	0.24	0.20	0.15
1.0 MONTH	0.38	0.27	0.21	0.17	0.15	0.12	0.10
AREAL VALUE (AREA 16.8 SQ KM 8 GAUGES)							
3.0 YEARS	1.34	1.08	0.85	0.70	0.59	0.46	0.38
1.5 YEAR	0.98	0.78	0.62	0.51	0.43	0.34	0.28
1.0 YEAR	0.86	0.68	0.54	0.44	0.38	0.30	0.25
0.5 YEAR	0.67	0.53	0.42	0.35	0.30	0.24	0.20
0.25 YEAR	0.57	0.41	0.32	0.27	0.22	0.20	0.15
1.0 MONTH	0.32	0.25	0.20	0.17	0.15	0.12	0.10
AREAL VALUE (AREA 21.0 SQ KM 10 GAUGES)							
3.0 YEARS	1.31	1.06	0.84	0.69	0.58	0.46	0.38
1.5 YEAR	0.95	0.77	0.61	0.50	0.43	0.34	0.28
1.0 YEAR	0.83	0.67	0.53	0.44	0.37	0.30	0.25
0.5 YEAR	0.64	0.52	0.41	0.34	0.29	0.24	0.20
0.25 YEAR	0.56	0.40	0.32	0.26	0.22	0.19	0.15
1.0 MONTH	0.30	0.24	0.20	0.17	0.15	0.12	0.10
AREAL VALUE (AREA 25.2 SQ KM 12 GAUGES)							
3.0 YEARS	1.30	1.05	0.84	0.69	0.58	0.45	0.37
1.5 YEAR	0.94	0.76	0.61	0.50	0.42	0.34	0.28
1.0 YEAR	0.81	0.66	0.52	0.43	0.37	0.30	0.24
0.5 YEAR	0.63	0.52	0.41	0.34	0.29	0.23	0.19
0.25 YEAR	0.47	0.38	0.31	0.25	0.23	0.18	0.15
1.0 MONTH	0.29	0.24	0.19	0.16	0.14	0.12	0.10

Table 6.5 Values of the constants a, b, c for calculation of the maximum rainfall intensities for different durations.

RETURN PERIOD	CONSTANTS		
	a	b	c

POINT VALUE (AREA 2.1 SQ KM 1 GAUGE)			
3.0 YEARS	22.2	9.1	-0.01
1.5 YEAR	13.3	7.4	0.04
1.0 YEAR	10.9	6.8	0.05
0.5 YEAR	7.4	5.9	0.06
0.25 YEAR	4.2	4.2	0.09
1.0 MONTH	2.5	4.0	0.06
AREAL VALUE (AREA 4.2 SQ KM 2 GAUGES)			
3.0 YEARS	12.3	11.3	-0.02
1.5 YEAR	13.7	9.4	0.03
1.0 YEAR	11.2	8.8	0.04
0.5 YEAR	7.4	7.4	0.06
0.25 YEAR	4.9	6.4	0.06
1.0 MONTH	2.4	5.1	0.06
AREAL VALUE (AREA 6.3 SQ KM 3 GAUGES)			
3.0 YEARS	23.3	12.6	-0.04
1.5 YEAR	14.1	10.7	0.02
1.0 YEAR	11.5	10.2	0.03
0.5 YEAR	7.9	9.2	0.05
0.25 YEAR	4.7	7.3	0.07
1.0 MONTH	2.8	6.7	0.04
AREAL VALUE (AREA 8.4 SQ KM 4 GAUGES)			
3.0 YEARS	25.9	15.0	-0.08
1.5 YEAR	15.5	12.7	-0.01
1.0 YEAR	12.0	11.5	0.02
0.5 YEAR	8.4	10.4	0.03
0.25 YEAR	5.4	9.4	0.05
1.0 MONTH	3.0	7.8	0.04
AREAL VALUE (AREA 16.8 SQ KM 8 GAUGES)			
3.0 YEARS	21.2	14.5	-0.01
1.5 YEAR	14.7	14.1	0.00
1.0 YEAR	11.8	13.2	0.03
0.5 YEAR	8.9	13.0	0.03
0.25 YEAR	4.6	8.2	0.07
1.0 MONTH	3.7	11.9	0.03
AREAL VALUE (AREA 21.0 SQ KM 10 GAUGES)			
3.0 YEARS	21.1	14.9	-0.01
1.5 YEAR	15.0	14.7	0.00
1.0 YEAR	12.2	14.1	0.02
0.5 YEAR	8.9	13.6	0.03
0.25 YEAR	4.6	8.2	0.06
1.0 MONTH	4.1	13.8	0.02
AREAL VALUE (AREA 25.2 SQ KM 12 GAUGES)			
3.0 YEARS	22.6	15.8	-0.04
1.5 YEAR	14.9	14.9	0.00
1.0 YEAR	12.7	14.8	0.01
0.5 YEAR	10.8	15.8	0.00
0.25 YEAR	6.9	14.6	0.02
1.0 MONTH	4.3	14.7	0.02

minutes. For example, a block rainfall with a duration of 20 minutes and an intensity of 0.45 mm/min has a return period of one year on a point-value i-d-f diagram. The same rainfall has a return period of about 2 years on a 25 sq.kms. i-d-f diagram.

6.6 Areal Variations of Rainfall Intensity

By means of rearranging the values from point and areal i-d-f relationships, the statistical areal reduction factors were developed for different durations and return periods. Factors for 3.0, 1.5, 1.0 and 0.5 years' return periods are shown in Figures 6.8 - 6.12, with duration as a curve parameter. Figures 6.13 - 6.16 show areal reduction factors with the return period as a curve parameter. It is interesting to notice that statistically derived areal reduction factors not only depend on duration, but also on the return period; this was previously called in question (Bell 1976). Table 6.6 lists the statistical area reduction factors for different durations and return periods.

In respect to all the analyzed rainfall durations, except that of 1 minute, the ARF-s increase with an increasing return period. Consequently, it can reasonably be concluded that the most intensive rainfalls (long return period) are the most limited in space. Such a sequence of dependency between ARF-s and return periods was observed by several researchers (Nguyen 1983, Lindholm 1983). With a storm duration of one minute, the ARF-s are only slightly dependent on the return period. However, an opposite to the sequence described above can be noticed for one-minute durations: one-minute ARF-s decrease with an increasing return period. This means that an area with a certain one-minute maximum intensity is bigger during high-intensive storms than an area with the same intensity during low-intensive storms. Such sequence of dependency between ARF-s and return period has not been observed before.

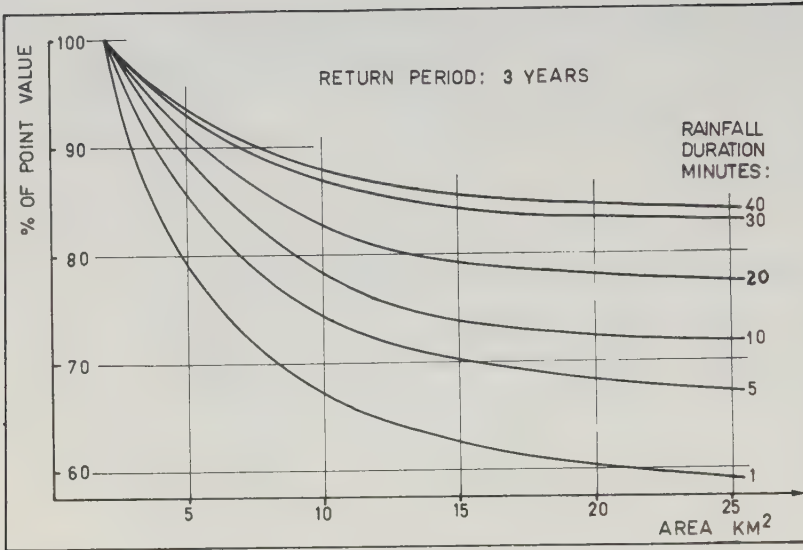


Figure 6.8 Statistical areal reduction factors.
Return period 3 years

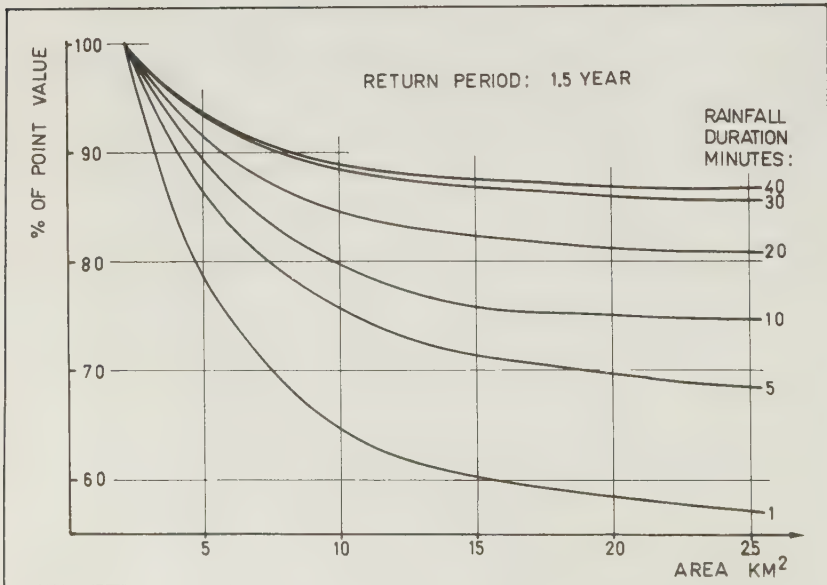


Figure 6.9 Statistical areal reduction factors.
Return period 1.5 year

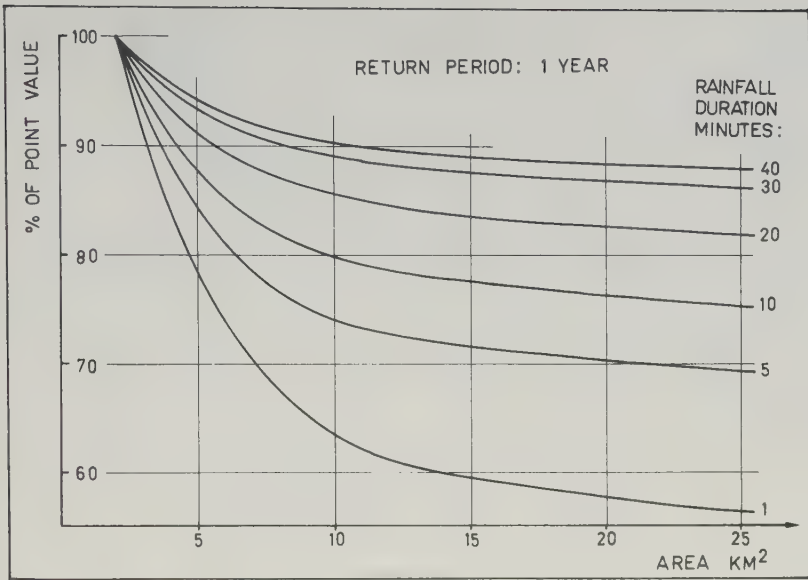


Figure 6.10 Statistical areal reduction factors.
Return period 1.0 years

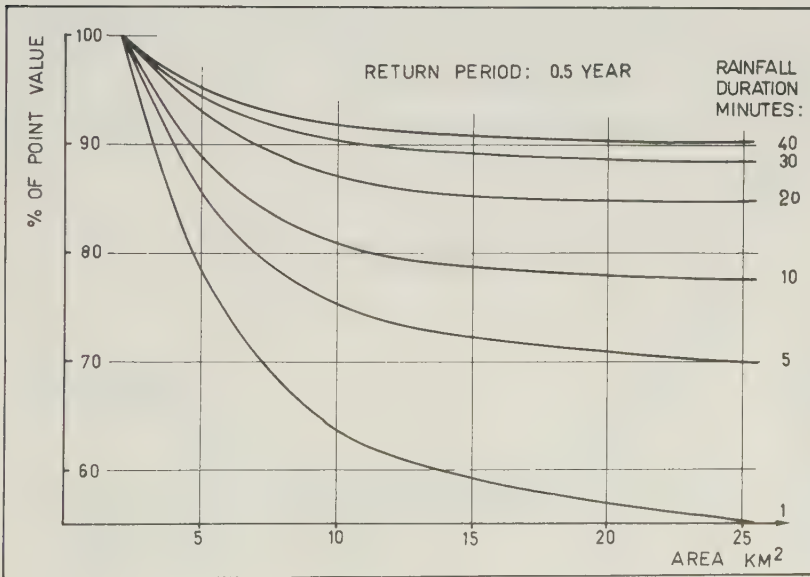


Figure 6.11 Statistical areal reduction factors.
Return period 0.5 years

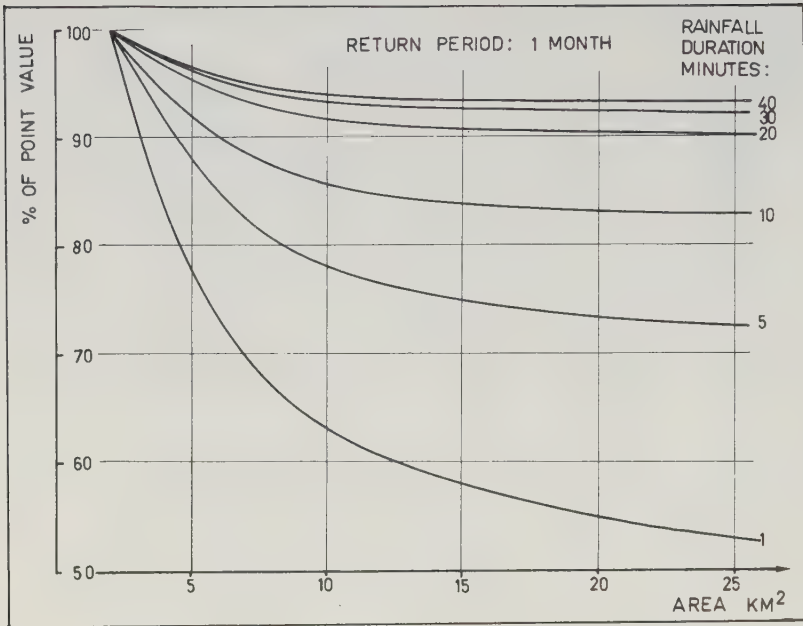


Figure 6.12 Statistical areal reduction factors.
Return period 1 month

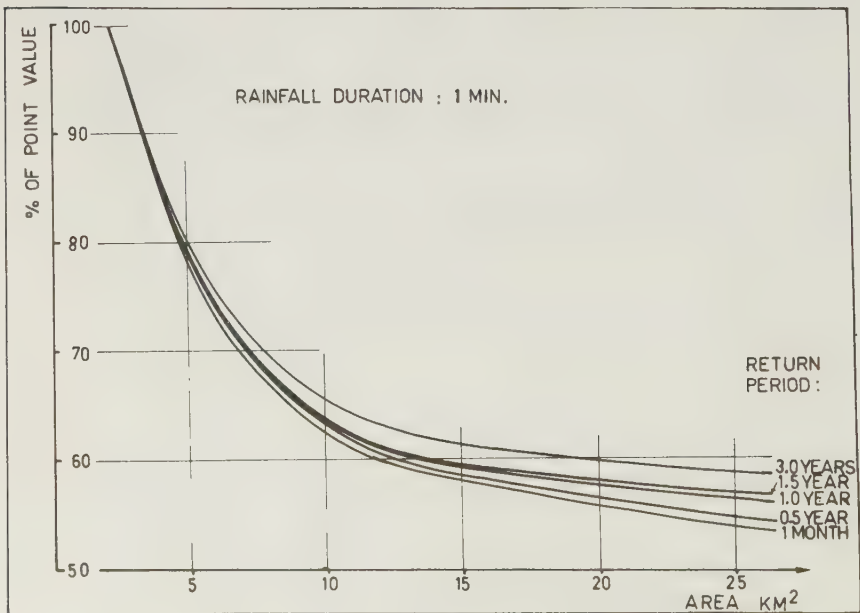


Figure 6.13 Statistical areal reduction factors.
Rainfall duration 1 minute

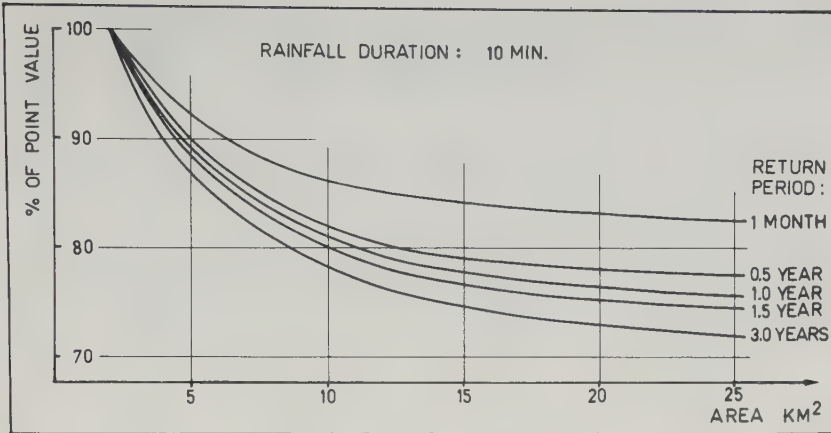


Figure 6.14 Statistical areal reduction factors.
Rainfall duration 10 minutes

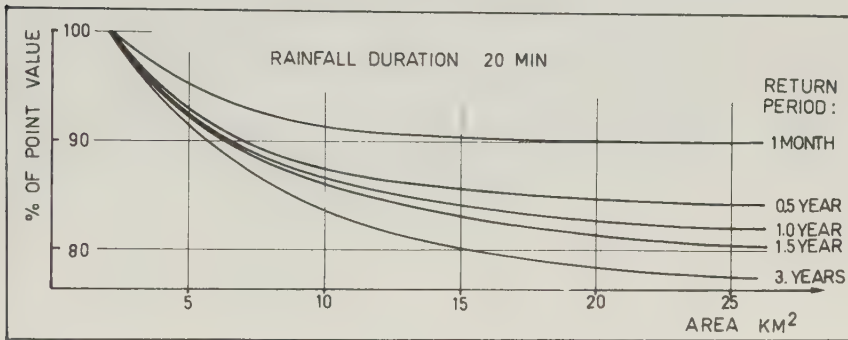


Figure 6.15 Statistical areal reduction factors.
Rainfall duration 20 minutes

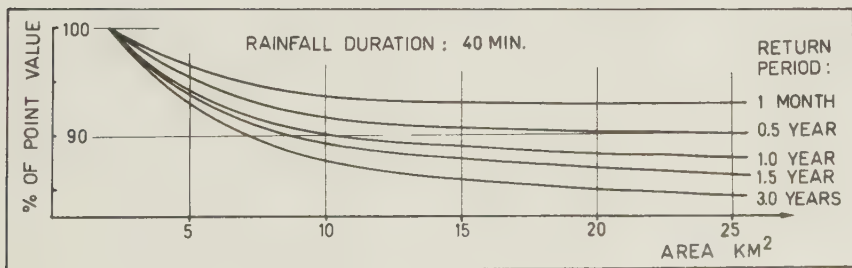


Figure 6.16 Statistical areal reduction factors.
Rainfall duration 40 minutes

Table 6.6 Statistical areal reduction factors.
(Areal rainfall intensities can be obtained
by taking given percentage of point values).

RETURN PERIOD	D U R A T I O N I N M I N U T E S					
	1	5	10	20	30	40
AREA 4.2 SQ KM 2 GAUGES						
3.0 YEARS	82.0	87.3	89.1	92.3	94.2	94.4
1.5 YEAR	82.1	88.0	90.1	93.0	94.4	94.7
1.0 YEAR	82.0	88.3	90.6	93.2	94.5	95.4
0.5 YEAR	82.1	89.0	91.5	94.0	95.1	95.9
0.25 YEAR	82.4	90.2	92.8	95.0	95.9	96.8
1.0 MONTH	82.9	91.3	94.5	96.3	96.9	97.2
AREA 8.4 SQ KM 4 GAUGES						
3.0 YEARS	69.7	78.8	82.5	86.4	89.2	90.1
1.5 YEAR	68.5	78.5	82.6	87.5	90.1	91.0
1.0 YEAR	68.0	74.5	83.1	87.9	90.7	91.8
0.5 YEAR	67.5	78.6	83.9	89.1	91.4	92.7
0.25 YEAR	67.6	79.0	85.1	90.8	93.0	93.8
1.0 MONTH	68.0	81.1	87.3	92.6	93.8	94.4
AREA 16.8 SQ KM 8 GAUGES						
3.0 YEARS	61.3	69.5	73.1	79.0	84.3	85.2
1.5 YEAR	59.7	70.6	75.6	81.7	86.6	87.3
1.0 YEAR	59.2	71.7	76.7	83.0	87.5	88.6
0.5 YEAR	58.4	71.8	78.8	85.1	89.1	90.4
0.25 YEAR	58.1	72.3	80.2	87.3	90.3	92.0
1.0 MONTH	57.2	75.1	84.0	90.8	93.0	93.5
AREA 21.0 SQ KM 10 GAUGES						
3.0 YEARS	59.6	68.2	72.2	78.0	83.6	84.5
1.5 YEAR	57.9	69.3	74.7	81.0	85.8	86.7
1.0 YEAR	57.2	69.8	75.8	82.2	86.6	88.2
0.5 YEAR	56.2	70.6	77.9	84.5	88.3	89.9
0.25 YEAR	55.2	71.3	80.4	86.4	89.7	91.8
1.0 MONTH	54.7	73.6	83.1	90.2	92.2	93.5
AREA 25.2 SQ KM 12 GAUGES						
3.0 YEARS	59.0	67.6	71.9	77.6	83.6	84.1
1.5 YEAR	57.1	68.8	74.4	80.8	85.8	86.7
1.0 YEAR	56.4	69.3	75.5	81.9	86.6	87.9
0.5 YEAR	55.2	70.2	77.3	84.5	88.3	89.9
0.25 YEAR	54.4	71.3	79.8	86.9	90.1	91.2
1.0 MONTH	53.4	73.0	82.7	90.2	92.2	93.5

6.7 Conclusions

Areal intensity-duration-frequency relationships supply different rainfall values than point i-d-f relationships. Areal rainfall intensity values are lower in respect to all durations and return periods.

If point i-d-f curves are used for deriving design storms, the error in average rainfall intensity and rainfall volume will be introduced into the simulation of runoff from real catchments.

The magnitude of error depends on duration, on the return period, and on the size of the catchment.

The most significant differences between point and areal rainfall values can be found where short durations and long return periods are concerned.

Factors reducing point rainfall values to areal values are given in this paper. The presented relationships will provide more realistic design storms in comparison with design storms derived from point i-d-f curves.

7. DYNAMIC PROPERTIES OF RAINFALL IN LUND

This chapter presents the methodology used in, and the results obtained from, studies of the dynamic properties of 400 short-term rainfalls observed in Lund during a period of three years. This chapter is, to a major extent, based on the following publications:

Niemczynowicz, J, Dahlblom, P (1984): "Dynamic Properties of Rainfall in Lund". Nordic Hydrology, 15(1), (pp 9-24).

Niemczynowicz, J (1984): "Areal Rainfall - An Improved Input for Modeling of Runoff". Proceedings of the Third International Conference on Urban Storm Drainage, Gothenburg, Sweden, June 4-8, (pp 335-344).

Niemczynowicz, J (1984): "Rainfall Movement and its Impact on Runoff". Proceedings of the Nordisk Hydrologisk Konferense, Copenhagen, Denmark, August 6-8, (pp 289-298).

7. DYNAMIC PROPERTIES OF RAINFALL IN LUND

7.1 Introduction

It is generally recognized that the shape of a runoff hydrograph depends not only on the catchment characteristics and the time distribution of the rainfall pattern, but also on the dynamic properties of the rainfall, such as the velocity and direction of the rainfall movement. This statement implies that rainfall-movement characteristics should be taken into account when choosing the rainfall input for runoff modeling. The possible range of impact of the rainfall movement characteristics on runoff generation can only be judged if the rainfall velocity and direction are known in statistical terms. This work aims to deliver such statistical information for the city of Lund. The probability distribution of rainfall velocities and the relative frequencies of the rainfall directions were studied on the basis of 400 rainfall events observed during a three-year period in the city of Lund.

In order to avoid misunderstandings, it is important that the terms "rainfall velocity" and "rainfall direction" be clearly defined. Since this study is focused on the runoff-generating process, we are only interested in the effects which can be observed on the ground. Accordingly, rainfall movement is defined as the velocity and direction of the water masses generated by rainfall, occurring in a sequence on the ground. This means that the true movement of clouds is not involved here. For example, stationary clouds generating rainfall in a distinct directionally oriented sequence will produce an effect on the ground which will be considered as a rainfall movement. This definition of rainfall movement has clear implications for the choice of rainfall-tracking method.

For calculations of storm velocity and direction, a special program has been developed. The statistical processing of the results was performed according to generally accepted statistical rules and with the aid of MINI-TAB programs.

7.2 The Data Base

The rainfall series from twelve gauges were divided into rainfall events with an arbitrarily chosen, 15-minute interval between events. High-intensity rainfalls being our main concern, all events with an average intensity of less than 2 mm/hour during 10 successive minutes were excluded from the data base. The velocity and direction of the rainfall movement were calculated for all remaining events whenever the maximum one-minute intensity exceeded 6 mm/hour. 400 rainfall events observed during the three-year period from 1979 to 1981 were included in the data base.

7.3 Triade-Program for Calculation of the Rainfall Velocity and Direction

A simple program, called TRIADE, for determining the velocity and the direction of storm movement has been developed. The algorithm for the determination of the velocity vector is a modification of a well-known three-point method (Hindi and Kelway 1977). The method requires that some easily recognizable characteristic be present in a rainfall pattern. In our case, the maximum intensity during one minute, observed at different gauges, was used as the characteristic. Once we know the time when this peak occurs for each gauge, the average velocity vector can be calculated, provided that all peaks denote the same rainfall cell. With regard to all gauges and events, the time to peak was chosen manually, directly from the rainfall-intensity lists.

If only one peak was observed for each raingauge, all time-to-peak values were accepted. The occurrence of more than one peak during the same event means that more than one rain-cell passed the network in some sequence. In this case, choosing the right combination of time-to-peak values is crucial to the correct estimation of the velocity vectors. The time-to-peak values were only accepted if they formed a clearly recognizable movement pattern. In respect to events with a great number of peaks, it was often difficult

to decide which of the time-to-peak values should be accepted as belonging to the same raincell. Here, a number of combinations of time-to-peak values were chosen. The final velocity vector was taken from that combination which showed the smallest variation of velocity vectors between all triads of gauges.

If the time-to-peak values for three arbitrarily chosen gauges are known, a velocity vector V can be calculated:

$$V = (v_1, v_2)$$

$$v_1 = \frac{\partial x_1}{\partial t}$$

$$v_2 = \frac{\partial x_2}{\partial t}$$

where (x_1, x_2) are the space coordinates for the gauges and t is the time-to-peak value. Introducing a three-dimensional space, where one axis is the time coordinate and the two others are the ordinary x_1 and x_2 coordinates, a plane can be placed through three points in the space:

$$r_1 x_1 + r_2 x_2 + r_3 = t$$

where

$$r_1 = \frac{\partial t}{\partial x_1} = \frac{1}{v_1}, \quad r_2 = \frac{\partial t}{\partial x_2} = \frac{1}{v_2}$$

and r_3 is a relative time parameter.

For each three-gauge combination, three simultaneously linear equations can be established:

$$r_1 x_{1i} + r_2 x_{2i} + r_3 = t_i, \quad i = 1, 2, 3$$

The system of simultaneous equations was solved by triangulation according to the Crouts method. The number of systems,

m , is equal to the number of three-gauge combinations from a number of gauges in operation n .

$$m = \binom{n}{3}$$

In our case $n = 12$ and $m = 220$ when all gauges are in operation. The solution of each of these sets of equations yields a vector R_j (the index j denotes a j -set of three gauges):

$$R_j = (r_{1j}, r_{2j})$$

with a length $\|R\|_j$:

$$\|R\|_j = \sqrt{r_{1j}^2 + r_{2j}^2} \quad j = 1, 2, \dots, m$$

The absolute value of velocity is then $\|V\|_j$:

$$\|V\|_j = \|R\|_j^{-1}$$

A value expressing the average velocity and direction for the whole area can now be calculated. The velocity of the event was taken as an average value based on all combinations of gauge triads:

$$\bar{V} = \frac{1}{m} \sum_{j=1}^m \|V\|_j$$

When calculating the average direction, we wanted to minimize the influence of the "wrong" vector, i.e. vectors calculated from triads of gauges for which the time-to-peak value did not belong to the same rainfall cell. Hence, the normalized vector were used:

$$R_j^* = \|R_j\|^{-1} \cdot R_j = \|V_j\| R_j$$

The sum of normalized directions

$$R^* = \sum_{j=1}^m R_j^*$$

was finally taken as an average direction of the event. For multi-peak events, a number of average velocities and directions were calculated.

Wrong combinations were eliminated by means of choosing the average vectors with the smallest variation between triads. As a measure of the range of variation, the length of the average vector was assessed:

$$S = \frac{1}{m} \left\| R^* \right\|$$

The value of S varies between 0, if velocity vectors are equally distributed over the circle, and 1, for the case when all vectors have the same direction. The direction with the smallest S value was accepted as being the final storm direction for the rainfall event.

Appendix 5 lists the TRIADE program.

The performance of the program was checked by means of comparing the results with previously calculated storm velocities and directions for extreme rainfall events in Lund (Niemczynowicz and Jönsson 1981b), using Marshall's method (Marshall 1980). A good agreement between the two methods was achieved. Further confirmation of the reliability of the results was obtained by correlating the calculated storm velocities and directions against observed wind velocities and directions.

7.4 Storm Velocity and Direction for 400 Rainfall Events

The average velocity of storms in the city of Lund is 10.35 m/s, based on calculations made for 400 rainfall events observed during a 3-year period. Figure 7.1 supplies relative frequencies, and Figure 7.2 presents the probability of non-exceedance of rainfall velocities. A two-parameter lognormal distribution fits the observed points well. The χ^2 -test yields a value $\chi^2 = 9.82$, and $r = 0.997$.

The average direction of storm movement, defined as the sum of normalized vectors, is 72 degrees counted clockwise from

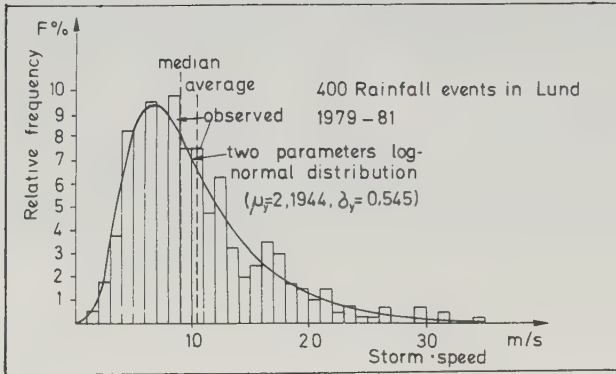


Figure 7.1 Relative frequency of storm velocity.
(Based on 400 events)

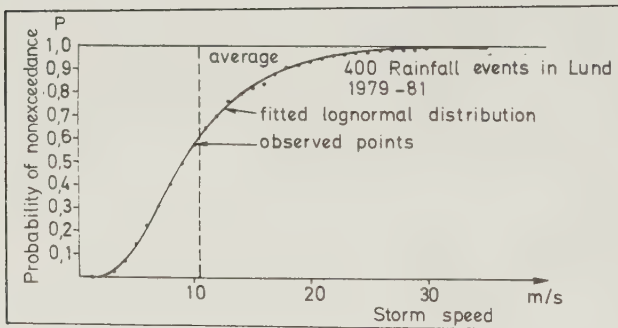


Figure 7.2 Probability of non-exceedance with regard to
storm velocity.
(Based on 400 events)

the north. The relative frequency of storm directions in 20-degree sectors is shown in Figure 7.3. Figure 7.4 demonstrates the relative frequency of rainfall direction in sectors with varying width. Note that two main directions of rainfall movement can be distinguished: the first towards the south-east, and the second towards the north-north-east. Rainfalls moving towards the south-west were very seldom observed. Appendix 6 lists storm movement parameters calculated for 400 rainfall events with the aid of a TRIADE program.

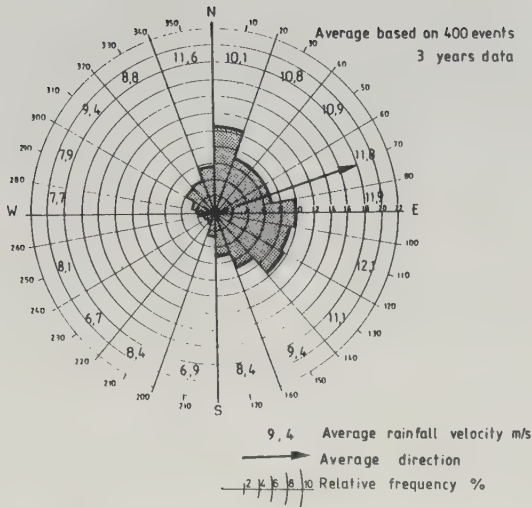


Figure 7.3 Relative frequency of storm direction.
(Based on 400 events)

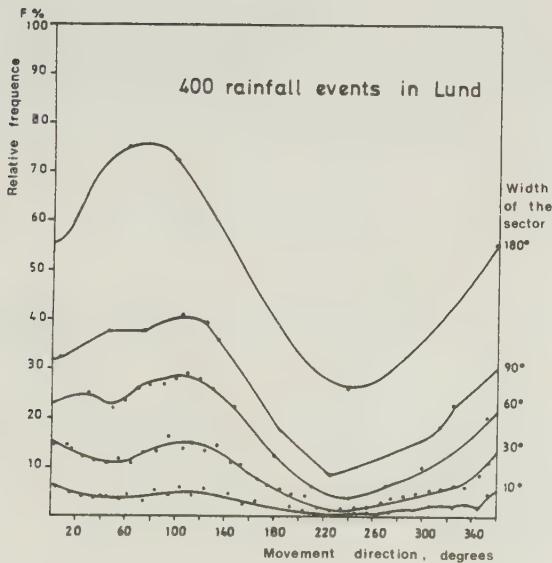


Figure 7.4 Relative frequency of storm direction in
sectors with varying width.
(Based on 400 events)

As the influence of storm movement on runoff depends on the joint effects of storm velocity and direction, it is interesting to know the relative frequency of storm velocity in different directions. Table 7.1 states the relative joint frequencies of storm velocity and direction in velocity and direction classes. It can be noticed that there is a distinct maximum of relative frequency around storm velocities 5.5 - 12.4 m/s and a storm direction towards the east and south-east.

Table 7.1 Relative joint frequencies of storm velocity and direction (%)

STORM DIRECTION DEGREES	S T O R M V E L O C I T Y m/s						ALL
	0.0- 5.4	5.5- 12.4	12.5- 17.4	17.5 22.4	22.5 27.4	≥27.5	
0-45	3.5	8.5	4.8	1.8	0.8	0.3	19.5
46-90	2.8	5.5	5.3	3.0	1.0	0.8	18.3
91-135	3.3	9.0	4.3	2.8	1.3	0.8	21.2
136-180	2.5	8.3	1.8	1.8	0.3	-	14.5
181-225	2.0	2.5	1.0	-	-	-	5.5
226-270	0.8	1.8	0.3	0.3	-	-	3.0
271-315	1.8	0.3	1.3	-	0.3	0.3	6.5
316-360	2.5	4.8	2.3	1.5	-	0.5	11.5
All	19.0	43.3	20.7	11.0	3.5	2.5	100.0

7.5 Relation Between Storm Movement and Storm Intensity

The entire data base was divided into six classes, based on a maximum 5-minute rainfall intensity. Table 7.2 shows the average velocities and directions in the entire data base and in the intensity classes. Figure 7.5 demonstrates the relative frequency of movement direction in the six intensity classes. Table 7.2 and Figure 7.5 clearly suggest that a dependency obtains between rainfall movement and rainfall intensity.

Table 7.2 Rainfall movement parameters for different rainfall maximum intensity classes

5 min MAX intensity classes mm/min	Number of events	Rainfall velocity					Rainfall direction degree from N
		Average	Stan	Median			
		m/s	dev	m/s	μ_y	δ_y	
0.00-2.36	400	10.35	5.65	9.03	2.194	0.545	71
0.00-0.10	89	11.03	5.60	9.87	2.284	0.490	62
0.11-0.16	99	10.52	5.94	9.32	2.196	0.576	85
0.17-0.26	91	10.96	6.29	9.08	2.240	0.575	78
0.27-0.45	52	9.19	4.17	8.37	2.125	0.432	76
0.46-0.74	39	9.86	5.19	8.77	2.140	0.578	34
0.75-2.36	30	8.53	5.22	6.51	1.975	0.595	21

where μ_y and δ_y are the mean and standard deviation of the natural logarithms of x = storm velocity m/s

The one-way analysis of variance performed on rainfall velocity versus rainfall intensity shows that the relation is significant on the 95% probability level. The regression equation is:

$$Y = 11.0 - 2.30 x ,$$

where Y is storm velocity in m/s and X is 5-min max intensity, $r = -0.323$, $N = 400$

Although the relation is weak, the regression equation and Table 7.2 indicate that high-intensity storms may have a low velocity, whereas low-intensity storms usually have high velocities. This rather unexpected conclusion can probably be explained by the specific climatic conditions in the southern part of Sweden. High-intensity storms usually occur in summer, when wind velocities are low. Strong winds, which can be observed on the ground level during high-intensive

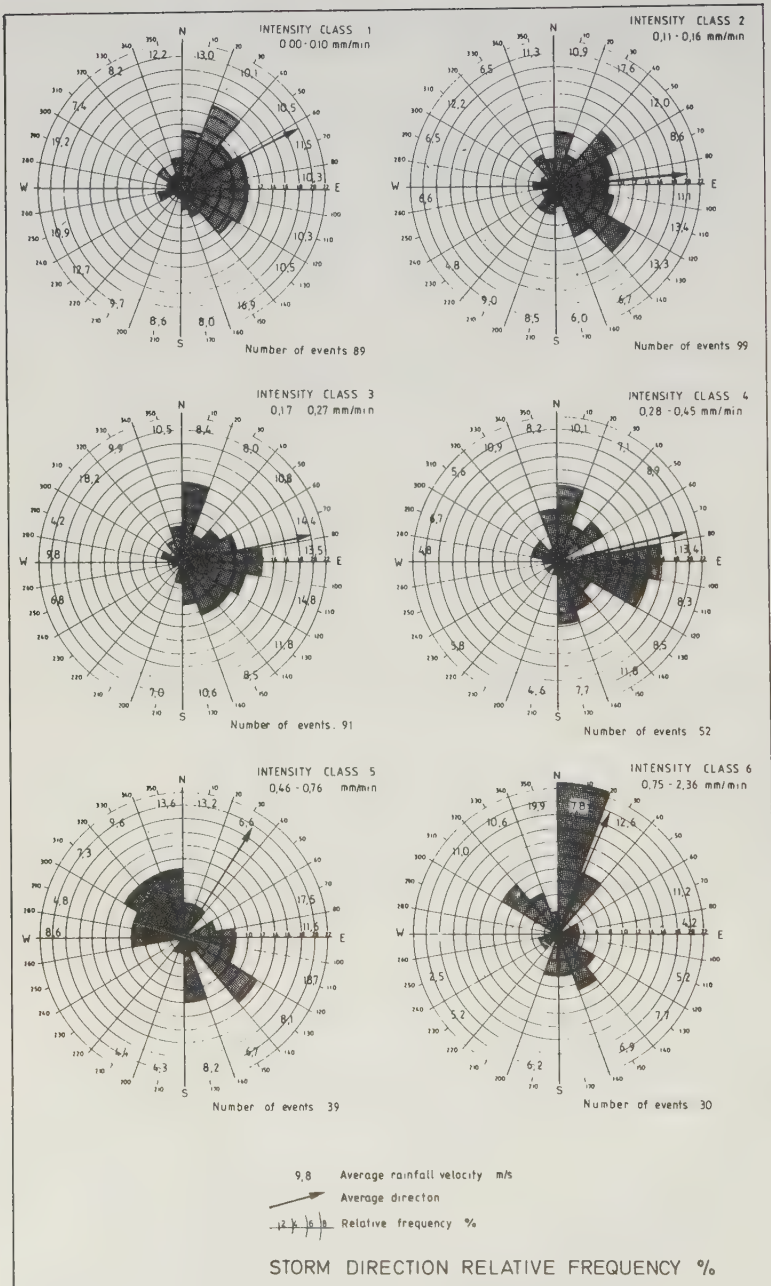


Figure 7.5 Relative frequency of storm direction in intensity classes (based on 400 events)

rainfalls such as thunderstorms, are probably generated by the storm itself and are unrelated to the wind velocities at high altitudes which govern the storm movement. It will be shown later that the correlation of wind velocities on the ground level and storm velocities is slight indeed.

Lognormal distribution also fits well to rainfall velocities in intensity classes. The parameters of lognormal distribution are shown in Table 7.2. The probability of nonexceedance with regard to storm velocity in intensity classes varies according to shown parameters for lognormal distribution. From Figure 7.5 it can be seen that the main direction of rainfall movement where high-intensity rainfalls are concerned is oriented towards the north-north-east.

7.6 Relation Between Storm Movement and the Season of the Year

The whole data base was divided into 4 classes with regard to the season of the year. Table 7.3 shows the average velocities and directions of the storm movement in 4 time classes. Figure 7.6 contains the relative frequencies of storm direction in time classes. From Table 7.3 and the figures, the general pattern of the relation can be seen. The conclusions from section 7.5 can be confirmed: low storm velocities occur most often during the summer months. Analysis of variance performed on storm velocity versus the month number shows that the relation is significant at the 99% probability level. Storm velocities in time classes were also found to be log-normally distributed: Table 7.3 supplies the parameters.

The storm movement during the summer months is mainly oriented towards the north-north-east; during the rest of the year, the main direction of movement is to the east.

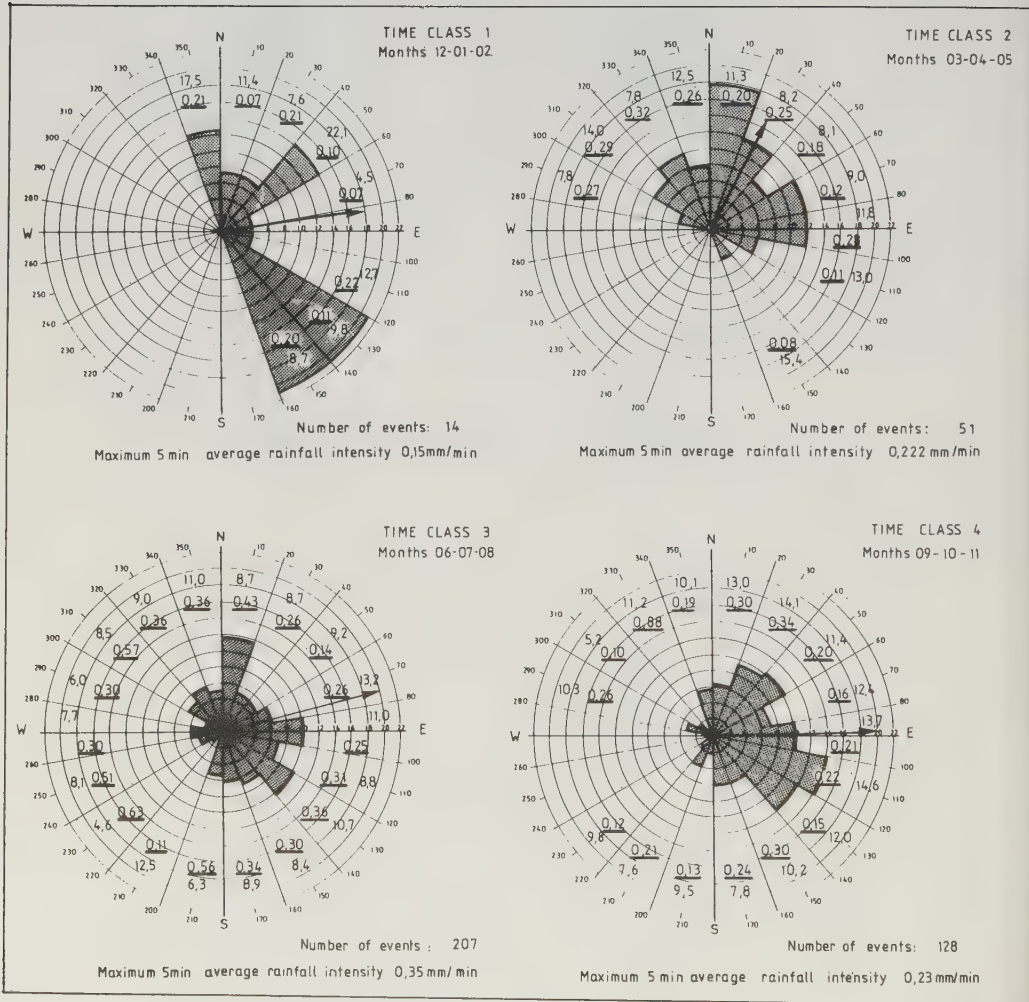


Figure 7.6 Relative frequency of storm direction in time classes (based on 400 events)

Table 7.3 Rainfall movement parameters for different seasons of the year

Period month	Number of events	Rainfall Velocity				Rainfall			
		Aver. m/s	St. dev.	Median m/s	μ_y	δ_y	Direct. Degree from N	Intens. Aver. mm/min	St. dev.
12-01-02	14	12.21	7.73	10.78	2.321	0.637	81	0.15	0.096
03-04-05	51	10.51	5.27	9.99	2.224	0.532	27	0.22	0.204
06-07-08	207	9.25	5.05	8.03	2.096	0.506	76	0.35	0.337
09-10-11	128	11.85	6.10	10.54	2.327	0.574	88	0.23	0.253

7.7 Relation Between Storm and Wind Movement

Wind data were available at Sturup airport, 17 kms SSE of Lund, and at Kastrup airport, 20 kms W of Lund. At Sturup, wind data refer to records of wind velocity and direction at the ground level, noted every 6 hours starting at 0100 hrs.

Kastrup data consist of wind velocity and direction registered at 800 mb, 700 mb and 600 mb height, approximately corresponding to altitudes 1200 m, 2200 m and 4500 m above sea level, registered every 6 hours starting at 0000 hrs. Wind parameters corresponding to rainfall events in the data base were chosen from nearest in time available wind record.

A total of 158 rainfall events, with corresponding wind data available for the period between May and September, were analyzed. Table 7.4 compares average rainfall and wind movement parameters and demonstrates that the wind velocity at all measured altitudes exceeds the rainfall velocity. There is good agreement between wind and rainfall movement direction. Wind velocities at all altitudes are lognormally distributed: the parameters of distribution are shown in Table 7.4. Figure 7.7 shows the relative frequency and probability of nonexceedance of wind velocity at 600 mb height.

Table 7.4 Comparison of rainfall and wind movement parameters.
(Based on 158 rainfall events)

	Rainfall velocity m/s	Wind velocity m/s				Rain- fall direc- tion	Wind direction Degrees from North			
		Ground level	800 mb	700 mb	600 mb		Ground level	800 mb	700 mb	600 mb
Average	9.89	5.81	10.92	11.58	12.47	65	60	66	58	59
St Dev	5.61	2.89	5.39	5.32	6.23					
Median	8.67	6.00	11.00	11.00	11.00					
μ_y	2.15	1.59	2.26	2.32	2.39					
δ_y	0.54	0.65	0.54	0.55	0.54					

Correlation coefficient between rainfall and wind movement parameters are supplied in Table 7.5. In order to avoid discrepancy due to circularity of directions, 360 degrees were added to the smaller of two values to be correlated when the difference was greater than 180 degrees.

Table 7.5 Correlation coefficients for wind and storm movement parameters. (Based on 158 events)

	Wind velocity				Wind direction			
	Ground level	800 mb	700 mb	600 mb	Ground level	800 mb	700 mb	600 mb
Storm velocity	0.144	0.507	0.611	0.647				
Storm direction					0.856	0.914	0.932	0.923
5-Min max intens	-0.301	-0.283	-0.205	-0.140				

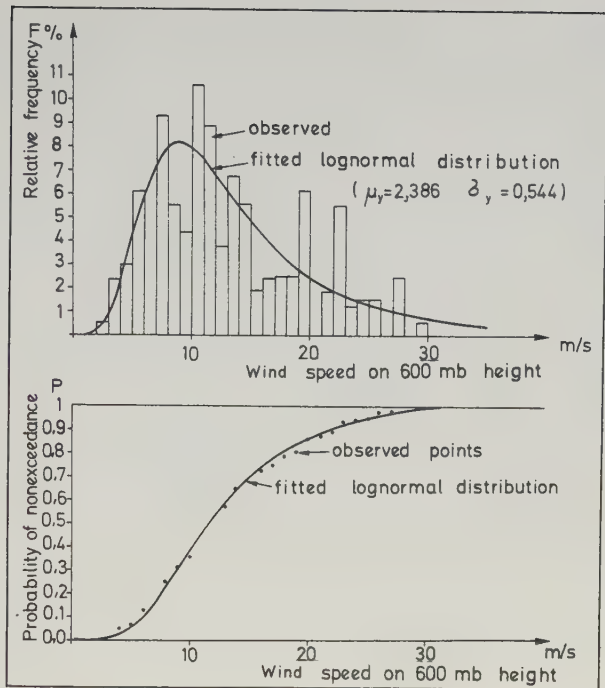


Figure 7.7 Relative frequency and probability of non-exceedance for wind velocity.
(Based on 158 events)

Table 7.5 shows that there is, in general, good correlation between storm and wind movement parameters, with the exception of storm velocity and wind velocity at the ground level.

The storm velocity correlates best with wind velocity at the highest altitude, 600 mb height. The best correlation for storm direction is observed with the wind direction at 700 mb height. A similar relation has been observed before by several researchers (Shearman 1977, Marshall 1980). Figure 7.8 shows the relation between rainfall velocity and wind velocity at 600 mb height. For comparison, Figure 7.9 shows the same relation with regard to wind velocity at the ground level. It is clear that there is practically no relation between storm and wind velocity at the ground level, if all 400 rainfall events are subjected to analysis (correlation coefficient $r = 0.144$). In the case of high-intensity

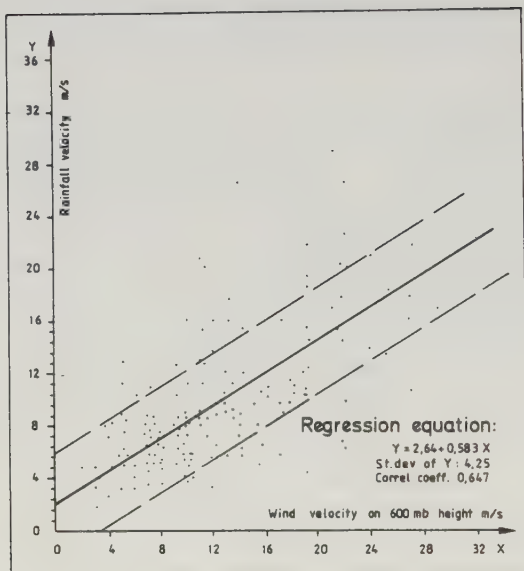


Figure 7.8 600 mb wind velocity versus storm velocity

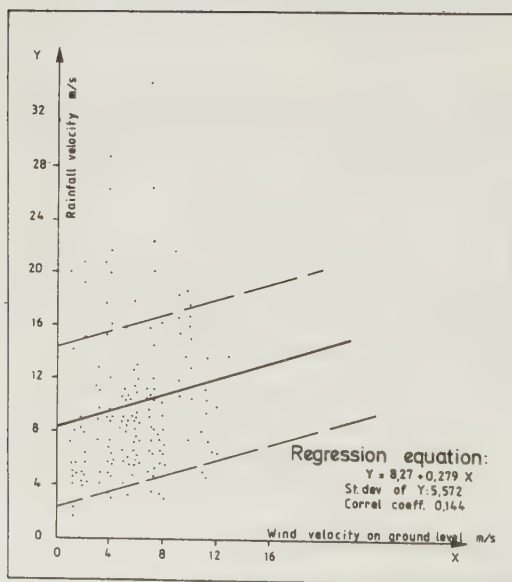


Figure 7.9 Ground level wind versus storm velocity

storms, though, the correlation coefficient between storm and wind velocity at the ground level increases slightly; for 32 storms with a 1-minute maximum intensity exceeding 1 mm/min, the correlation coefficient is $r = 0.286$.

Additionally, in Table 7.5, the correlation coefficients between wind speed and maximum 5-minute rainfall are stated. The observed correlation is weak; but the minus sign indicates that the relation which was observed between storm velocity and maximum storm intensity is also valid for the relation between wind velocity and maximum storm intensity. Table 7.6 contains the significance levels for the relations between wind and rainfall movement parameters. Figure 7.10 shows the relation between storm and wind direction at 700 mb height.

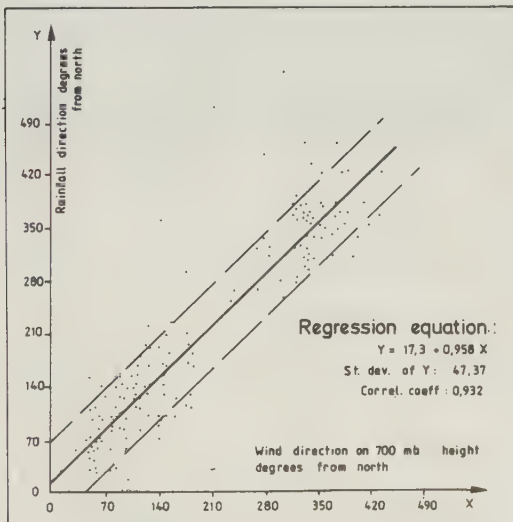


Figure 7.10 700 mb wind direction versus storm direction.
 (Based on 158 events)

Table 7.6 Significance levels for relations between storm and wind movement parameters

	MONTH No	VELO- CITY	S T O R M DIREC- TION	MAX INTENS.	W I N D			
					VELOCITY GROUND 700 LEVEL mb		DIRECTION GROUND 700 LEVEL mb	
STORM VELOCITY	***							
STORM DIRECTION		**						
STORM MAX INT.	***	*	○					
WIND VEL. GROUND	***	*	***	***				
WIND VEL. 700 mb	***	***	*	***	***			
WIND DIR. GROUND		*	***	***	***	*		
WIND DIR. 700 mb		***	***	***	***	***	***	

where : *** - significance on 99.9 % probability level,
 ** - significance on 99.0 % probability level,
 * - significance on 95.0 % probability level,
 ○ - not significant.

7.8 Conclusions

1. The results of this study confirm that information about rainfall movement does exist in a set of data from a network of point measurements. If the network is sufficiently dense, and the time resolution of registration is sufficiently good, the rainfall movement parameters can be extracted from the data with the aid of a relatively simple procedure.
2. Observed good correlations between storm and wind movement parameters indicate that the simple method of computing storm velocities and directions which has been employed here is sufficiently good for practical applications. Since this method calculates the storm velocity on the basis of time-to-peak values, it is possible that obtained velocities might be underestimated. If we assume that observed wind velocities at the 800 mb height should, on the average, be equal to the storm speed, then we can estimate the average error to be about 10%.
3. 700mb wind is a very good indicator of storm movement. Most airports measure wind at this level. Airport wind data can be used in rough estimations of storm movement parameters.
4. Storm velocity and wind velocity distribution at different levels fits well to lognormal distribution.
5. Two main directions of rainfall movement can be clearly distinguished: the first, prevalent for most of the year except in summer, is oriented towards the west and south-west. Rainfalls moving in this direction usually possess average or low intensities and high velocity. The second main direction of storm movement is oriented towards the north-north-east. Storms moving in this direction mainly occur during the summer months; they are characterized by high intensities and low velocities.

6. The results obtained in the course of the analyses possess clear practical implications. The analysis of storm velocities indicates that the rainfall events with high intensities, which are the most pertinent ones where various practical applications are concerned, may have lower-than-average velocities. On the average, though, these velocities are much higher than the velocities of water flow which usually occur in sewers. Thus the "worst" situation, when the storm velocity equals the velocity of flow, has a low probability of occurrence. Probabilities of nonexceedance of storm velocities are given in this chapter. Those relative frequencies of storm movement direction that have been reported here can be used in judging the probability of "worst" events when the main direction of sewers in the catchment coincides with the most probable direction of the storm movement. Catchments whose sewers are basically oriented towards the north-north-east can expect that this "worst" event may happen.
7. Further investigations, presented in chapter 8, will quantify the impact of rainfall movement on the runoff-generating process. This question is crucial with regard to the necessity of taking the dynamic properties of the rain into account when choosing rainfall input for the simulation of runoff. The range of storm movement parameters given here is a necessary basis for answering this question.

8. INVESTIGATION OF THE INFLUENCE OF RAINFALL MOVEMENT ON RUNOFF HYDROGRAPH

This chapter presents the results of a study aiming to quantify the influence of rainfall movement on the runoff-generating processes. The practical implications are strongly stressed. This chapter is, to a major extent, based on the following publications:

Niemczynowicz, J (1984): "Investigation of the Influence of Rainfall Movement on Runoff Hydrograph - Part 1, Simulations on Conceptual Catchment". Nordic Hydrology, No 15 (2) (pp 57-70).

Niemczynowicz, J (1984): "Investigation of the Influence of Rainfall Movement on Runoff Hydrograph - Part 2, Simulations on Real Catchments in Lund". Nordic Hydrology, No 15 (2) (pp 71-84).

8. INVESTIGATION OF THE INFLUENCE OF RAINFALL MOVEMENT ON RUNOFF HYDROGRAPH

(An attempt to quantify the possible range of influence on real catchments)

8.1 Introduction

The influence of rainfall movement on the shape of the runoff hydrograph has been recognized for a long time. Rainstorms travelling downstream on the catchment, along the main direction of the conduits, produce higher peaks and steeper limbs of the hydrograph than storms moving upstream. In the following text, this effect will be referred to as the maximal directional bias, defined in the following terms:

$$\text{MAX DIRECTIONAL BIAS} = \frac{\text{QPDOWN} - \text{QPUP}}{\text{QPUP}} \quad 100 \quad (\%)$$

where: QPDOWN - peak flow for storms moving downstream
 QPUP - peak flow for storms moving upstream

The reason for this definition is the fact that the main interest of this study is focused on the greatest possible effect of the storm movement alone on the peak discharge. This maximal effect, or the greatest difference between the peaks, will occur when the storm moves in opposite directions: downstream and upstream. If the peak observed during downstream storm movement is, for example, 10 cum/s, and the corresponding value for upstream movement 5 cum/s, we will have a maximal directional bias equal to 100% according to the definition. The greatest directional bias occurs if the storm moves with the same velocity as the velocity of water flow down the catchment.

Since flow on real catchments consists of both overland and channel flow components, the geometric properties of the land surface and the sewer system will influence the average velocity of flow.

Most previous studies have been performed either in laboratories using rainfall simulators (for example Townson and Ong 1974), or with the aid of mathematical runoff models applied to hypothetical drainage areas (for example Surkan 1974). More recent studies on the dynamic properties of rainfall have primarily focused on developing methods for calculating the storm velocity and direction from data gathered from a dense network of gauges (Marshall 1975, Shearman 1977, Hindi 1977).

To our knowledge, no studies have been performed regarding the significance of the directional bias for practical applications, such as the design of the sewer network. Nor have any studies of directional bias been made on the basis of statistics concerning the rainfall movement on real catchments. The reason for this is that a long series of rainfall data from a dense network of gauges, with good time synchronization, is necessary for making statistics of rainfall movement. Moreover, the desired series of good areal rainfall data must be combined with a thorough knowledge of the catchment parameters, if the influence of rainfall movement on the runoff hydrograph is to be investigated.

An attempt to quantify the directional bias was made by James and Drake (unpublished) for the Hamilton, Ontario, urban area. The authors strongly emphasize that the dynamic properties of rainfall influence the shape of the runoff hydrographs, and if one does not account for this effect, an error will be introduced into the modeled runoff. Unfortunately, the Hamilton study was done without convincing statistical support in respect to the storm movement parameters and runoff characteristics. The crucial question concerning the necessity of including the dynamic properties of the rain in practical rainfall-runoff calculations remained unanswered.

The raingauge network of 12 gauges has operated in Lund since 1978 and delivers good quality rainfall data. The data of three years were used in deriving statistical areal reduction

factors and drawing up statistical descriptions of rainfall movement over the city of Lund. A description of the data collection and processing systems has been given before (Falk et al 1979, Niemczynowicz and Jönsson 1981b, Niemczynowicz 1982a). A computer program for the purpose of determining the velocity and direction of storm movement has been developed, and the results have been used in calculating the probability distribution of storm directions, the probability of non-exceedance of storm velocities, and the joint probability of storm velocity and direction (Niemczynowicz and Dahlblom 1984).

The scope of this chapter consists in the use of previously calculated statistical parameters of rainfall movement in Lund for a quantitative description of the influence of storm movement on runoff from several real catchments. Different factors affecting the magnitude of directional bias will be described. We will, first of all, search for the combination of those factors which gives the maximum effect on directional bias. Finally, we will combine rainfall movement statistics with the modeled runoff and state the probability distribution of directional bias for different catchments in Lund.

The question of whether the dynamic properties of rainfall must be considered when choosing rainfall input for runoff modeling can only be answered if the range of effect is defined in statistical terms. The presented paper aims to supply the necessary basis for answering this question.

8.2 Factors Influencing Peak Discharge

The magnitude of directional bias depends on a number of factors which can be divided into two groups. The first is related to the rainfall characteristics, the second is related to the geometric and hydraulic characteristics of the catchment. All factors in both groups can, theoretically, be variable over a very wide range, but in practice we have to deal only with a limited range of these factors, defined, for example, by intensity-duration-frequency (i-d-f) relationships or real catchment characteristics.

Dimensional analysis of factors influencing the runoff hydrograph (Yen and Chow 1969, Townson and Ong 1974) shows that non-dimensional, relative peak discharge can be defined as follows:

$$\frac{Q_p}{IA} = f \left(\frac{V_r}{I}, \frac{T I}{L}, \frac{t}{T}, \frac{B}{L}, \frac{D}{L_c}, S_s, S_c, \frac{K}{L} \right) \quad (1)$$

where:

Q_p - peak discharge	B - width of catchment
I - rainfall intensity	L - length of catchment
A - area covered by moving storms during duration T	D - diam. of conduits
V_r - rainfall velocity	L_c - length of conduits
t - start discharge time	S_s - surface slope
T - rainfall duration observed at a point	S_c - conduit slope
	K - roughness length

if we neglect terms accounting for temperature, kinematic viscosity and the effect of the distribution of raindrops.

The first 3 terms represent the effect of the momentum, energy and mass inputs of the rainfall, whereas the next 5 terms represent the effect of the geometry and topography of the catchment (Yen and Chow 1969).

It is obvious that the peak flow discharge depends on storm velocity in relation to flow velocity. But the flow velocity depends on both rainfall and catchment characteristics, and it changes during one event; thus, it cannot conveniently be used as an independent parameter. Choosing independent parameters according to equation (1), we have the possibility of separating rainfall-dependent parameters from catchment-dependent parameters, the last ones being constants for one particular catchment.

At first, we want to clarify the relation between rainfall characteristics and peak discharge. In this case, for the given catchment, equation (1) will be reduced to:

$$\frac{Q_p}{I A} = f \left(\frac{V_r}{I}, \frac{T I}{L}, \frac{t}{T} \right) \quad (2)$$

Obviously, the function f will be different for different directions of storm movement in relation to the direction of conduits. Since we are only interested in the situation where the directional bias is maximal, we will consider two extreme directions in relation to the main direction of conduits: downstream and upstream direction. We can now split the equation (2) into two separate equations for these two directions:

$$\frac{Q_{pUP}}{I A} = f_1 \left(\frac{V_r}{I}, \frac{T I}{L}, \frac{t}{T} \right) \quad (3)$$

$$\frac{Q_{pDOWN}}{I A} = f_2 \left(\frac{V_r}{I}, \frac{T I}{L}, \frac{t}{T} \right) \quad (4)$$

where:

Q_{pUP} - peak discharge for upstream storm movement
 Q_{pDOWN} - peak discharge for downstream storm movement
 and the storm characteristics in equation (3) and (4) denote storm movement upstream and downstream respectively.

Since we are not, for the moment, interested in the time pattern of the runoff hydrograph, and L is constant, we can relate the relative peak discharge for both downstream and upstream storm movement to the relative storm velocity V_r/I only and plot these relationships using storm duration T as a curve parameter. With these relationships, the peak flow pertaining to both downstream and upstream storm movement can be calculated for any combination of storm movement parameters. The relative peak discharge relates to rainfall intensity and duration by different functions. It would be very difficult to derive these relations from observed rainfall events, because the intensity and duration cannot be clearly defined. At first, we therefore used rainfall with constant intensity during its duration ("block rains").

8.3 Directional Bias Simulated for a Conceptual Catchment

In order to minimize the costs of computer runs, we chose to investigate the general form of the relations on a simple, conceptual catchment with geometric and hydraulic parameters similar to the respective parameters of the real catchment in Lund. The conceptual catchment consists of 12 subcatchments with a total area of 50 ha and 30% imperviousness each. The subcatchments are connected to each other by 12 identical conduits, each with a length of 460 m, a diameter of 2.0 m and slope of 0.004 (see Figure 8.1).

The geometry of the conceptual catchment seems to be simple in comparison with real catchments. Still, if we want to simulate the runoff process in a realistic way, the simulation model must account for important physical processes which influence the shape of the runoff hydrograph. Therefore, the Storm Water Management Model (SWMM) was used in the simulations. The SWMM was modified so that data from 12 gauges could be used as rainfall input.

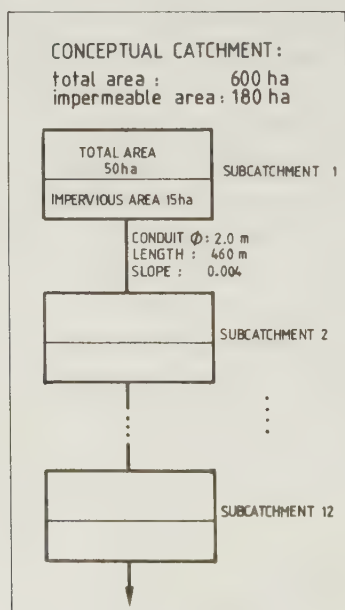


Figure 8.1 Schematic representation of conceptual catchment used for developing the relationships between peak discharge and storm movement parameters

The Runoff and Transport Blocks of the SWMM model were run using block-rain input with intensities between 5 and 100 mm/h. and durations between 2 and 100 minutes. Both over-land flow and conduit flow were calculated by the Runoff and Transport Blocks of the SWMM, a Manning equation being combined with a continuity equation. Surface losses on both impermeable and permeable surfaces were calculated as a specified value of depression storage which is extracted from the rainfall volume at the beginning of the storm. The infiltration on permeable surfaces is calculated according to the Horton equation with specified parameters. Rainfall movement was simulated by lagging the uniformly distributed rainfall stepwise over the 12 subcatchments, with a time step chosen in accordance with the required storm velocity. Downstream and upstream storm movement was simulated by reversing the time sequence of rainfalls occurring on opposite subcatchments.

8.3.1 Relationship Between Relative Storm Velocity and Relative Peak Discharge

Results from about 100 SWMM runs were used in plotting the relations between relative peak discharge and relative storm velocity for downstream and upstream storm movement. These plots are shown in Figures 8.2 and 8.3. Simulation runs were performed with storm velocities of 2 m/s, 4 m/s and 8 m/s respectively. Each simulation was run twice, with storm direction downstream and upstream. The rain input consisted of simple block rainfalls with the constant intensity I during the duration T .

Some scatter of observation points can be noticed on both plots. The reason for this scatter is that the rainfall parameters involved in the terms on the plot axis are not exactly defined with regard to all the runs. We assume that there is no runoff from permeable surfaces, an assumption which is often valid for real catchments. Here, though, some runoff from permeable surfaces can occur during runs with high rainfall intensity and long duration. Therefore, the

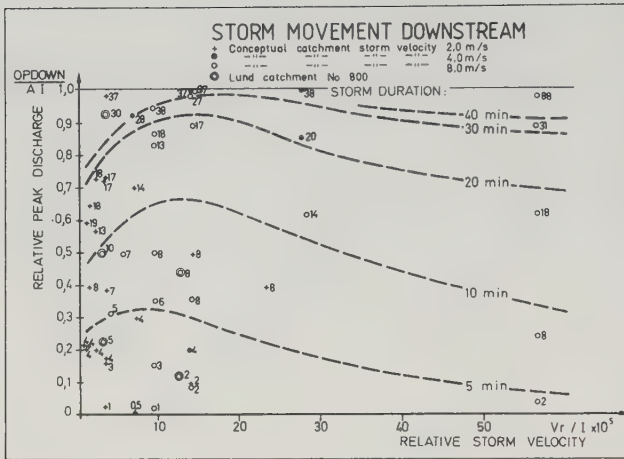


Figure 8.2 Relation between relative peak discharge and relative storm velocity for downstream storm movement

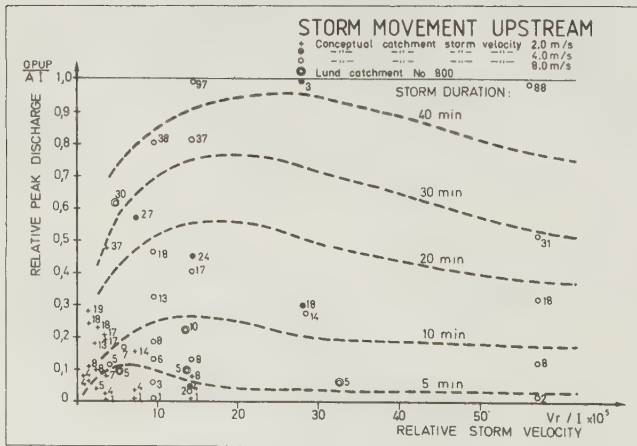


Figure 8.3 Relation between relative peak discharge and relative storm velocity for upstream storm movement

resulting contributing area A may differ slightly from one run to the next. Besides, the effective rainfall intensity on permeable surfaces is not the same as the one pertaining to impermeable surfaces. The storm duration, used as a curve parameter, was adjusted for the time of filling up the depression storage; but even this parameter is not always exactly defined because the model produces runoff directly, without depression storage, on 25% of all impermeable surfaces. Consequently, the plots of the relationship between relative storm velocity and relative peak discharge, shown in Figures 8.2 and 8.3, can only be used as a rough approximation to this relationship. Further refinement of the accuracy of the relation is not worth striving for as it is only valid for one particular imaginary catchment.

In spite of the inaccuracies mentioned above, both plots present a clear picture of the relationship.

The relations shown in Figures 8.2 and 8.3 are only valid for our particular catchment: in different catchment, with different parameters such as roughness, length of overland flow, surface slope etc, the relationship may not be the same. However, since the parameters chosen for this conceptual catchment are similar to those of the real catchment, we can expect that the general shape of the relations will also be similar. For comparison, the points obtained from runs on a real catchment in Lund are shown in Figures 8.2 and 8.3. These points fit quite well. From both graphs, the peak flow for downstream and upstream storm movement can be calculated for any combination of storm parameters.

8.3.2 Relationship Between Storm Duration and Directional Bias

Maximal directional bias can be expected if the storm velocity is equal to the flow velocity in a conduit. However, the flow velocity in a conduit is a function of flow discharge and it changes during the runoff event and between events. Therefore, the storm velocity was compared to the

full conduit flow velocity, which was assumed to be equal to the average flow velocity. Due to the shape of the relationship between flow velocity and discharge in respect to a given conduit, the error in the estimation of average velocity is small if the flow does not decrease below $1/3$ of the full-conduit flow. The rain input for the simulation runs was chosen in such a manner that this condition was fulfilled. The average flow velocity for the conceptual catchment was 3 m/s. Simulation runs were performed with storm velocities of 2 m/s, 4 m/s and 8 m/s respectively.

Now we can rearrange the observed points and show the relation between the directional bias and the storm duration for different storm intensities and for any particular storm velocity. Figure 8.4 shows this relationship for a storm velocity of 2 m/s, and Figure 8.5 for a storm velocity of 8 m/s.

Figures 8.4 and 8.5 show that the relationship is rather complicated and that the shape of the relationship changes drastically if the storm velocity changes. If the storm velocity is approximately equal to the average flow velocity (Figure 8.4), the directional bias increases when the rainfall intensity decreases; this is the case with all durations. The maximal bias for all intensities occurs when the duration is short, of the order of 3-5 minutes. The maximal simulated bias was about 500% for a rainfall intensity of 10 mm/h and a duration of 5 minutes. Where smaller intensities are concerned, one may expect to obtain even higher directional-bias values. These cases, however, are of limited practical importance, the discharge being relatively small.

If the storm velocity is higher than the average flow velocity (Figure 8.5), the relationship has an opposite sequence: low intensities generally provide a smaller maximal bias than high intensities. Maximal bias occurs at different durations with different intensities. In this case, the maximal bias of about 190% was simulated for the maximal intensity that was used, 100 mm/h with 5 minutes' duration. It is worth noticing that - as was to be expected - the magnitude of the

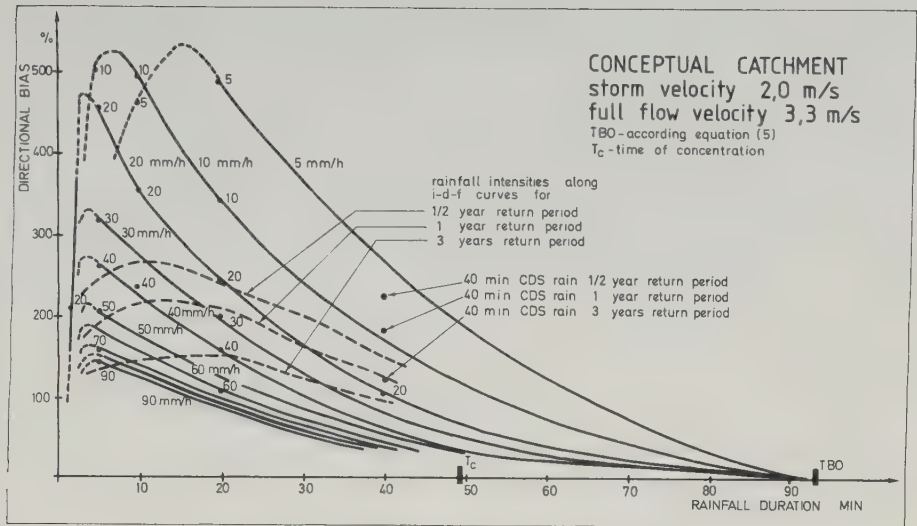


Figure 8.4 Relationship between storm duration and directional bias for storm velocity of 2 m/s

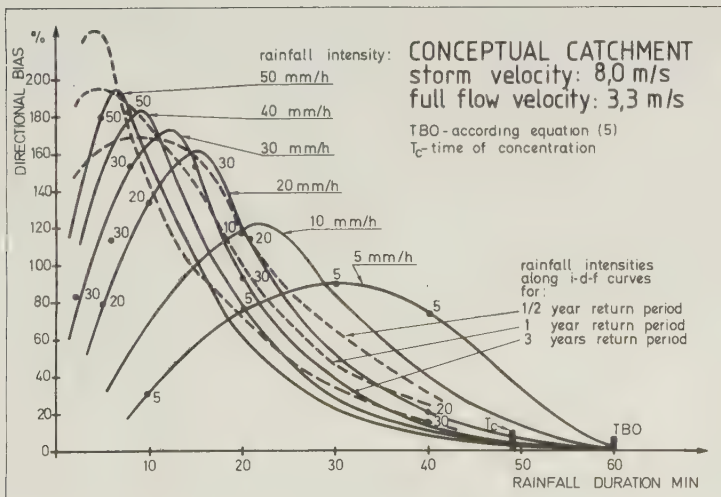


Figure 8.5 Relationship between storm duration and directional bias for storm velocity of 8 m/s

directional bias decreases as the storm velocity increases above the average flow velocity. In addition, it should be pointed out that the directional bias tends towards zero if the rainfall duration approaches a certain value. The value of duration when the bias is equal to zero (TBO) depends on the time of concentration for the catchment (T_c), the storm velocity (V_r), and the length of the catchment (LA) in the following manner:

$$TBO = T_c + \frac{LA}{V_r} \quad (5)$$

Equation (5) simply says that there will be no difference with regard to peak flow for down- and upstream storm movement, if the storm duration is sufficiently long for steady-state conditions to develop in both cases.

We can also calculate the width of the storm band (LRO) (or the diameter of a storm cell in real cases), necessary for the occurrence of the conditions described above.

$$LRO = LA + T_c V_r \quad (6)$$

In this case, TBO equals 93 minutes for a storm velocity of 2 m/s. and 60 minutes for a storm velocity of 8 m/s. assuming the same value of T_c equal to 49 minutes in both cases.

The width of the storm band LRO would be 11160 m for 2 m/s. and 28800 m for 8 m/s. storm velocity. Such large dimensions are more typical of so-called Small Mesoscale Areas (Austin and Houze 1972) than of single rainfall cells. Therefore, we can conclude that the conditions that are necessary for the directional bias to equal zero never occur in practice.

8.3.3 Directional Bias Simulated for Rainfalls Along the Intensity-Duration-Frequency Curves

In order to connect the directional bias values with a return period, we can follow the relationship along the i-d-f curves. When the storm velocity is equal to the average flow velocity (Figure 8.4), the lines along the i-d-f curves have distinct maxima for durations longer than those of the observed absolute maximum of directional bias. Maximal bias occurs with rainfall durations varying between $1/5$ and $1/3$ of the time of concentration, if the rainfall intensity is chosen along the respective i-d-f curves. It is worth noticing that the sequence of curves describing the directional bias along the i-d-f curves is "favourable" from a practical point of view: storms with a longer return period have a lower bias than storm with a short return period. In other words, maximal directional bias will occur for small rainfall events which do not cause any problems. The same sequence was observed when the so-called Chicago design storm (CDS-storm, Keifer and Chu 1957) was used as rainfall input (see Figure 8.4).

The respective relationship for storm velocities greater than flow velocity (Figure 8.5) present the opposite sequence; the directional bias reaches its highest value in the case of rainfalls with long return periods. The rainfall duration for maximal bias varies between $1/10$ and $1/6$ of the time of concentration. Table 8.1 shows the maximal directional bias for different storm velocities and return periods.

8.3.4 Directional Bias Versus Conduit Slope

All the values presented in Table 8.1 are obviously valid for our particular catchment only. As can be seen from equation (1), flow discharge also depends on the geometric and hydraulic parameters of the catchment and the sewer network. An investigation of the influence of all included parameters would require a great number of runs. Instead, we assumed that our real catchments in Lund would react in a manner similar to that of the conceptual catchment since the parameters

Table 8.1 Maximal directional bias simulated on the conceptual catchment

Storm Input	Storm durat. min	Storm intens. mm/h	Return period years	Maximal bias %	Time max bias/ time concentr.
Storm Velocity 2.0 m/s					
Block rain	12	28.8	1/2	265	0.24
Block rain	15	33.0	1	207	0.31
Block rain	18	47.5	3	142	0.37
Storm Velocity 4.0 m/s					
Block rain	12	28.8	1/2	200	0.24
Block rain	12	37.8	1	195	0.24
Block rain	11	77.2	3	187	0.22
Storm Velocity 8.0 m/s					
Block rain	12	28.8	1/2	164	0.24
Block rain	8	48.9	1	180	0.16
Block rain	6	88.2	3	192	0.13
Storm Velocity 2.0 m/s					
CDS-storm*	40		1/2	222	
CDS-storm*	40		1	182	
CDS-storm*	40		3	120	

* "Chicago Design Storm" (Keifer and Chu 1957)

we chose are similar. Only one parameter - one whose great importance was intuitively felt - was tested, namely the slope of the conduit. Figure 8.6, which describes the relationship between conduit slope and directional bias, shows that in the case of block rain with a return period of 1 year and a duration of 15 minutes, a maximum is obtained which corresponds to conduit slopes on the conceptual catchment and on the catchments in Lund.

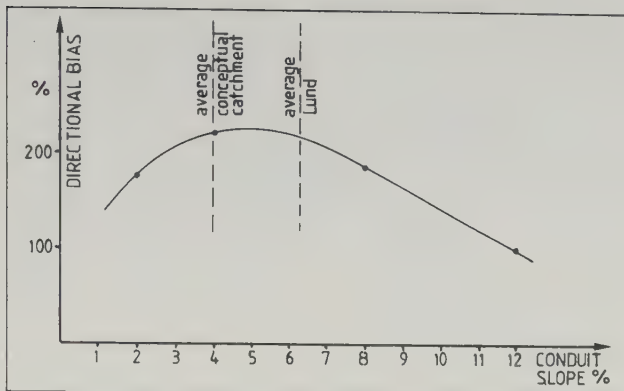


Figure 8.6 Conduit slope versus directional bias for 1-year block rain with 15 min duration.

(Storm velocity 2.0 m/s, full-flow velocity 3.3 m/s)

Figure 8.7 - 8.8 supply some examples of runoff hydrographs for downstream and upstream storm movement in cases where the observed directional bias was large. Hydrographs for stationary storms are included for comparison.

8.3.5 Summarizing Conclusions

Now we can draw some summarizing conclusions which will apply to real catchments with a range of parameters which is similar to that of the conceptual catchment:

1. The maximal directional bias can be expected to occur with storms moving downstream on the catchment, the velocity being equal to the average flow velocity.
2. The maximal directional bias can reach values of several hundred percent, but this occurs in storms with short duration and has no practical importance.
3. With regard to rainfalls with intensities and durations following the i-d-f curves, the maximal directional bias will occur at a duration related to the time of concentration. This duration can be roughly estimated as 1/5 to 1/3 of the time of concentration for the catchment.

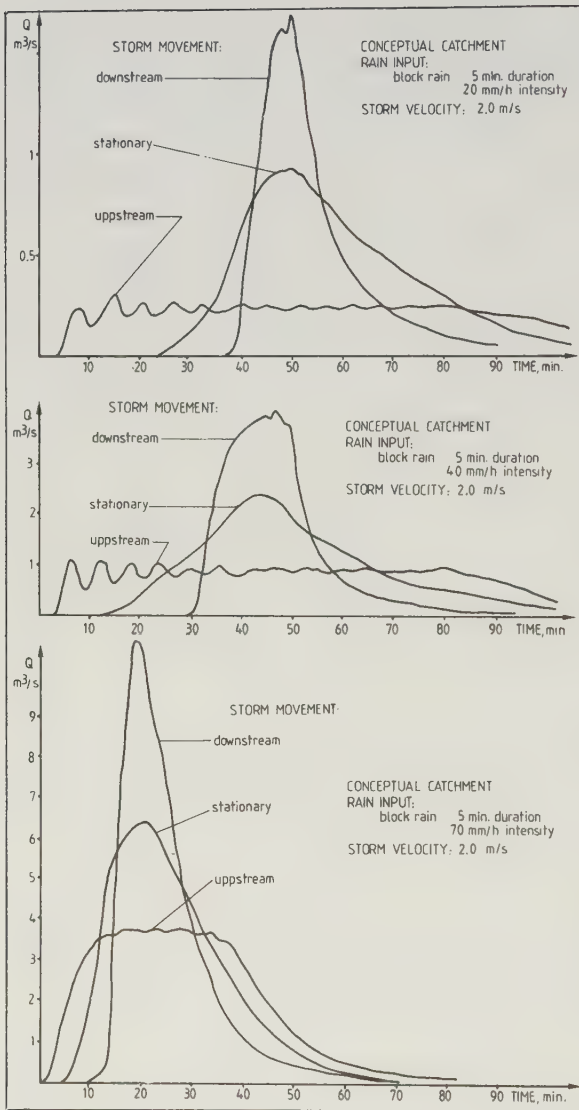


Figure 8.7 Runoff hydrographs for downstream and upstream storm movement. Storm duration of 5 minutes

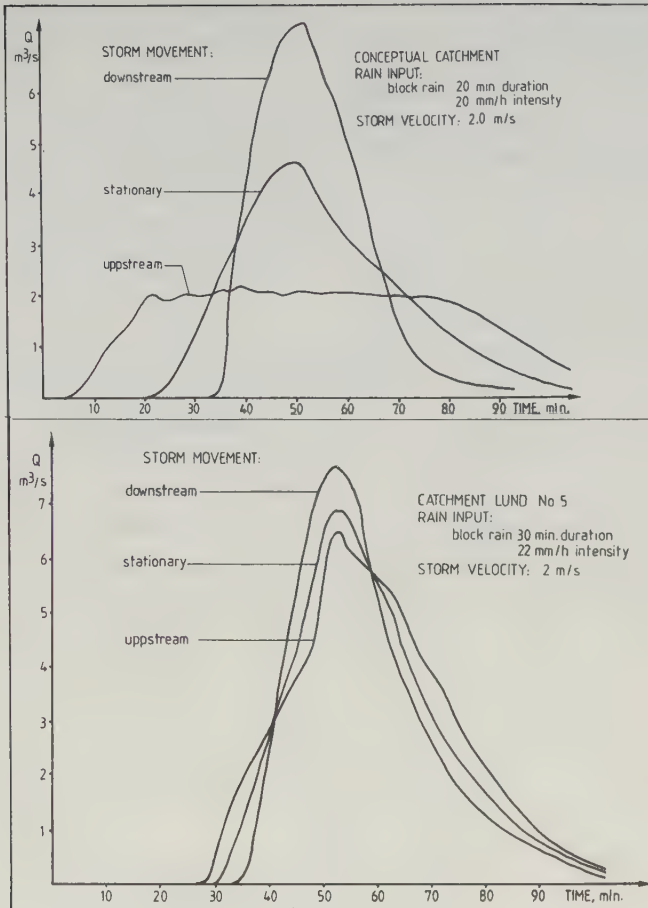


Figure 8.8 Runoff hydrographs for downstream and upstream storm movement

4. The typical conduit slopes that occur in Lund come within the range of slopes which cause the maximal directional bias.
5. The simple, linear geometry of the conceptual catchment was designed to maximize the directional bias. The maximal directional bias for real catchment with more compli-

cated networks of conduits will probably be lower than that which was simulated for the conceptual catchment.

Now we can examine the real catchments in Lund and check our conclusions with a smaller number of runs. At first, block rainfalls will still be used.

8.4 Drainage System in Lund

The storm water system in Lund can be divided into two major parts: the first, situated in a central part of the town, was built before 1950 and consists of combined sewers: the second part, successively built during the last 30 years, mainly consists of separated storm water conduits. Between the two parts of the system there are 9 main overflow structures. The total tributary area of both parts of the system is 1992 ha with an average imperviousness of approximately 30%.

The total area of Lund can be divided into 6 main catchments with a separated sewage system, and one area with a combined system (Figure 8.9). Figure 8.10 contains a schematic representation of the sewage system. As the whole area of the city of Lund slopes towards the south-west, most of the conduits are oriented in this direction and drain to the small river Hölje. One exception is catchment No 6 (see Figure 9.9), which is oriented towards the north-west.

Previously, during the so-called "Lund project", runoff from the stormwater system in Lund was measured at 5 outlets, stormwater being collected from about 90% of the total area of the city over a period of 17 months (Hogland and Niemczynowicz 1979, 1980). The whole area of the city was mapped and all the parameters needed for runoff simulation were collected. A thorough calibration of the Storm Water Management Model on 5 catchments with a separated system was performed.

For the purpose of the present study, the total area of the 5 separated catchments and of the combined part of the system

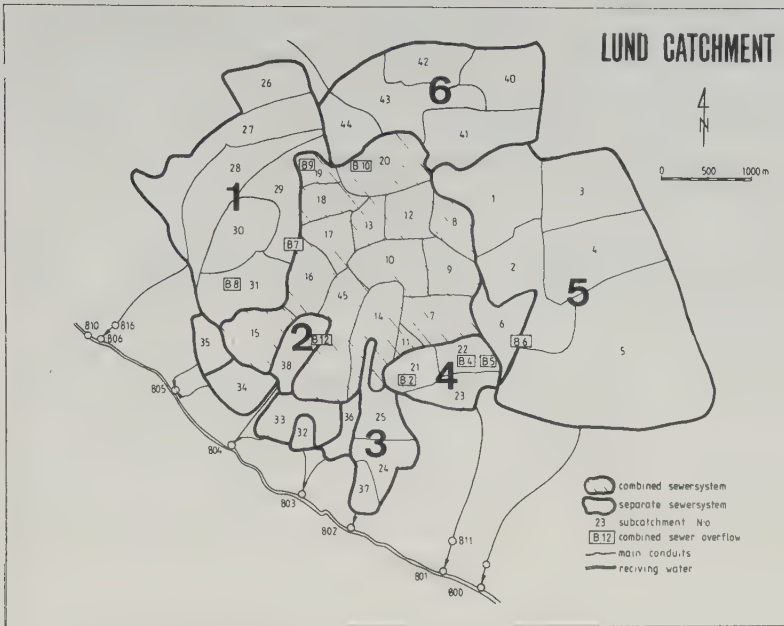


Figure 8.9 Segmentation of the Lund catchment

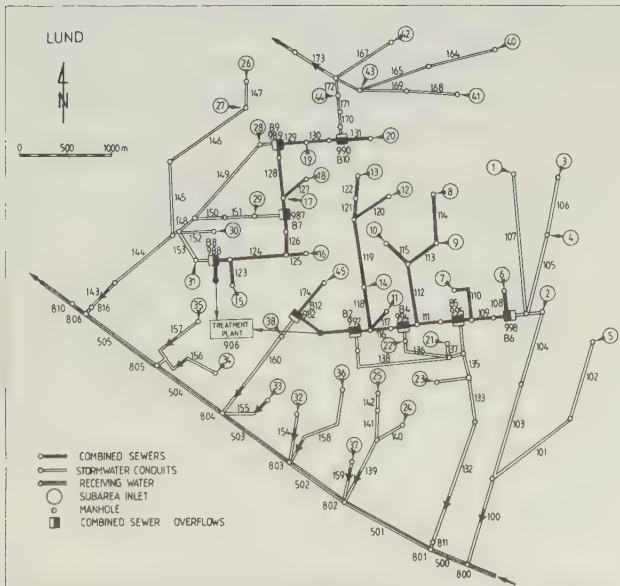


Figure 8.10 Schematic representation of the sewage system in Lund

was matched together, so that one run of the SWMM simulates runoff from the whole city, excluding catchment No 6. Simulated runoff hydrographs are listed at the stormwater outlets, numbered on the scheme (Figure 8.10), No 800 to 816, and at the outlet from the combined system, No 906.

8.5 Directional Bias Simulated on the Real Catchments in the City of Lund

Different catchments in Lund vary with regard to conduit geometry. The greatest directional bias can be expected to occur on a long catchment with conduits going straight along the long axis of the catchment. Catchment No 5, draining into outlet No 800, is the longest and has fairly straight conduits. This catchment shows the greatest directional bias. Other catchments are also generally oriented towards the south-west; but several smaller conduits occur at right angles to this direction. The simulated directional bias for these catchments was always smaller than for catchment No 5.

Simulations have shown that catchment No 3 yields a reversed directional bias; storms moving downstream give a smaller peak discharge than storms moving upstream. This amazing effect can be explained by the geometric properties of the conduit system. There are two main conduits draining the catchment, one short and flat and the other longer and steeper. The runoff from the upstream part of the catchment appears first at the outlet, while runoff from the downstream part comes later. This causes the reversal in respect to directional bias. All the irregularities with regard to conduit geometry that have been mentioned above reduce the effect of directional bias. To locate the situations which lead to maximal directional bias, we will take a closer look at catchment No 5 draining to outlet No 800.

8.5.1 Directional Bias Simulated Using Block Rainfalls

According to conclusions drawn from studies performed on the conceptual catchment, maximal directional bias will be expected to occur with a storm velocity equal to the average flow velocity, and with storm durations of about 10-15 minutes, if the rainfall intensity is chosen in accordance with the relevant i-d-f relationship. A number of runs performed with "block rainfalls" as input confirm this conclusion.

Figure 8.1 shows the relation between rainfall duration and the directional bias simulated for catchment No 5, with outlet No 800, for rainfalls of 1/2, 1 and 3 years' return period. The maximal directional bias of 87% is observed for the rainfall with a duration of about 10 minutes and a one-year return period. 10 minutes' duration is approximately equal to 1/3 of the time of concentration for catchment No 5. The relation does not show the characteristic shape observed for the conceptual catchment because the average storm velocity used in simulations does not usually match average flow velocity. Flow velocity varies significantly with flow discharge, which in turn depends on the magnitude of the rainfall input. Flow velocity also varies in different parts of the catchment. Therefore, the relationship has a mixed character, involving elements from cases of storm velocity that are under and over the velocity of flow.

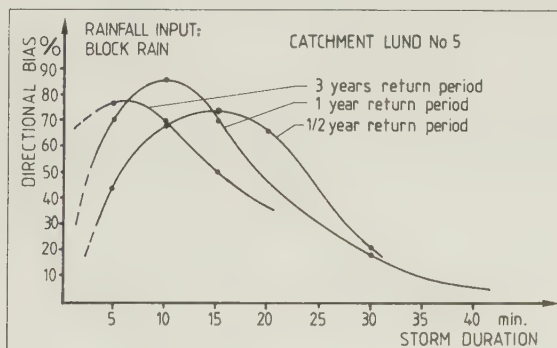


Figure 8.11 Relationship between rainfall duration and directional bias for "block rain" with different return periods. Catchment No 5 in Lund

Figure 8.12 contains the directional bias as a function of rainfall duration for different catchments in Lund. Catchment No 5 shows maximal directional bias.

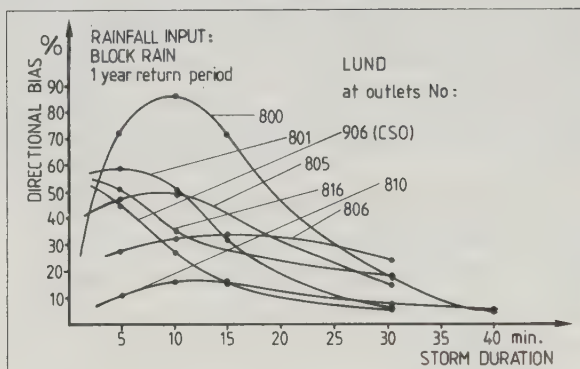


Figure 8.12 Relationship between rainfall duration and directional bias for "block rain" with a one-year return period. Different catchments in Lund

Figure 8.13 shows the relationship between storm velocity and directional bias for rainfall with 10 minutes' duration and a 1-year return period. The maximal directional bias is observed around a storm velocity of 4 m/s, which is approximately equal to the weighted average flow velocity for catchment No 5.

8.5.2 Directional Bias Simulated Using Observed Rainfall Events

Now we know the range of the values pertaining to maximal bias which can be expected for several catchments in Lund when block rain is used as input. The next question which we will try to answer is what order of magnitude of directional bias can be expected with real, observed rainfall events. Rainfall data registered from 12 gauges in Lund contain the information about rainfall movement. Rainfall velo-

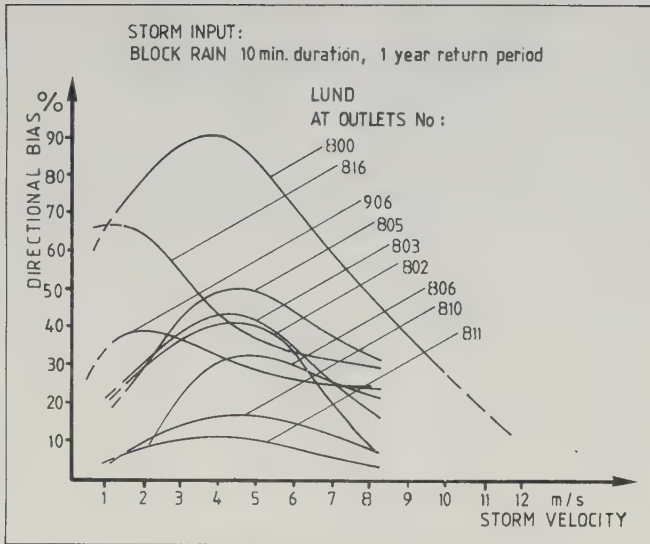


Figure 8.13 Relationship between storm velocity and directional bias on Lund catchment No 5

city and direction have been calculated previously for 400 rainfall events (Niemczynowicz and Dahlblom 1984). From this material, we have chosen a number of events where the direction of rainfall movement came close to paralleling the main direction of conduits on catchment No 5. Hyetographs for 12 gauges were assigned to the nearest subareas within the city of Lund, and the SWMM was run in order to calculate the runoff hydrograph for the observed, natural storm movement direction. The opposite storm movement direction was then simulated by reversing the time sequence for each hyetograph. Figures 8.14 - 8.15 show examples of runoff hydrographs, simulated with observed rainfall events as input, with natural and reversed directions of storm movement.

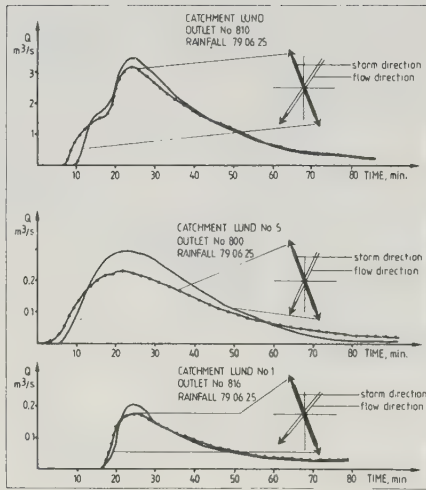


Figure 8.14 SWMM - simulated runoff hydrographs for an observed rainfall event. Rainfall 79 06 25

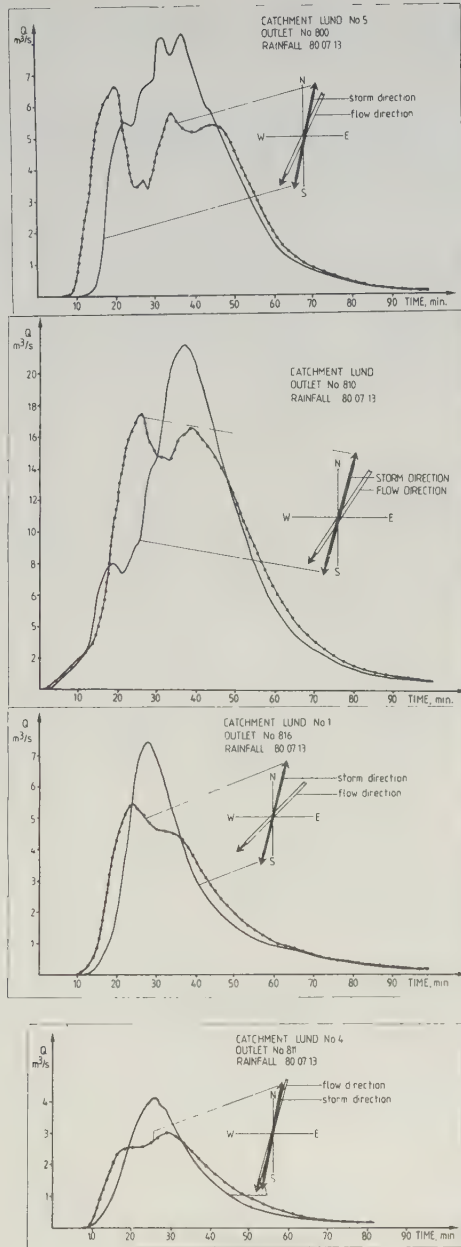


Figure 8.15 SWMM - simulated runoff hydrographs for an observed rainfall event. Rainfall 80 07 13

Table 8.2 lists the values of directional bias simulated for Lund catchment No 5.

Table 8.2 Directional bias values with varying rainfall input, simulated for Lund catchment No 5 (outlet No 800)

Storm input	Storm veloc. m/s	Storm durat. min	Storm intens. mm/h	Return period years	Maximal bias %	Tmax bias/ T conc.
Block rain	4.0	5	44.4	1/2	43	
Block rain	4.0	10	31.8	1/2	68	
Block rain	4.0	15	25.2	1/2	72	0.43
Block rain	4.0	20	21.0	1/2	65	
Block rain	4.0	30	16.2	1/2	22	
Block rain	4.0	5	57.6	1	70	
Block rain	4.0	10	42.0	1	88	0.29
Block rain	4.0	15	33.0	1	70	
Block rain	4.0	30	20.4	1	18	
Block rain	4.0	5	93.0	3	78	0.20
Block rain	4.0	10	70.2	3	67	
Block rain	4.0	15	55.2	3	50	
Block rain	1.5	10	42.0	1	80	0.29
Block rain	2.0	10	42.0	1	73	
Block rain	8.0	10	42.0	1	43	
Rain 790625	19.0				28	
Rain 800713	4.0				33	
Rain 800823	5.2				18	
Rain 800824	5.2				25	
Rain 800822	8.0				30	
Rain 800706	1.8				21	
Rain 800709	8.8				8	

It can be seen from Figures 8.14 - 8.15 and Table 8.2 that the directional bias observed with real storms is generally smaller than that of design storms. This effect was obviously to be expected, as the design storms were chosen in such a manner that the directional bias would be maximized. Observed storms, on the other hand, were never completely parallel to the conduits; and their duration and intensity were not necessarily close to those which produce maximal bias. The velocity of most rainfall events was higher than the flow velocity in conduits. Still, significant values regarding directional bias were simulated for real catchments and observed rainfall events.

8.6 Probability Distribution of Directional Bias for the City of Lund

We now know the magnitude of the possible directional bias which can be expected for the respective catchments in Lund. Maximal bias will only occur if a rainfall with a certain specific duration and intensity moves with a certain velocity exactly parallel to the direction of conduits. There is a certain probability that storms move with this velocity and direction. Knowing the direction of conduits for any catchment in Lund, we can therefore derive the probability of exceedance of the certain directional bias value where this catchment is concerned. The necessary statistics about rainfall movement parameters for the city of Lund have been derived previously by means of an analysis of storm direction and velocity, calculated on the basis of 400 rainfall events (Niemczynowicz and Dahlblom 1984).

Table 8.3 shows the joint probability of storm direction and velocity for the city of Lund.

According to the definition in section 8.1, the directional bias value describes the difference in peak flow between storms moving down- and upstream. Theoretically, the directional bias ranges from 0 to infinity. In relation to stationary storms, the peak flow can be higher or lower if we use moving rainfall as input.

Table 8.3 Joint probability of storm movement direction and velocity for the city of Lund

Storm direction degrees	S T O R M V E L O C I T Y m/s						All
	0.0- 5.4	5.5- 12.4	12.5- 17.4	17.5- 22.4	22.5- 27.4	> 27.5	
00- 45	0.035	0.085	0.048	0.018	0.008	0.003	0.195
45- 90	0.028	0.055	0.053	0.030	0.010	0.008	0.183
91-135	0.033	0.090	0.043	0.028	0.013	0.008	0.212
136-180	0.025	0.083	0.018	0.018	0.003	-	0.145
181-225	0.020	0.025	0.010	-	-	-	0.055
226-270	0.008	0.018	0.003	0.003	-	-	0.030
271-315	0.018	0.030	0.013	-	0.003	0.003	0.065
316-360	0.025	0.048	0.023	0.015	-	0.005	0.115
All	0.190	0.433	0.207	0.110	0.035	0.025	1.000

Because a stationary storm is the usual rainfall input for runoff modeling in most applications, it is interesting to examine cases where the peak flow exceeds the value observed when using stationary storms. In the following text, we will only consider cases where the peak flow can be higher than the one which occurs with stationary storms. The effect of storm movement on peak flow will be referred to as a dynamic bias, defined in the following terms:

$$\text{DYNAMIC BIAS} = \frac{\text{QPMOVING} - \text{QPSTAT}}{\text{QPSTAT}} 100\%$$

where:

QPMOVING is a peak flow for moving storms.

QPSTAT is a peak flow for stationary storms

The dynamic bias is positive when downstream storm movement is concerned (QPMOVING = QPDOWN) and negative when upstream storm movement is concerned (QPMOVING = QPUP). Theoretically, the dynamic bias ranges from minus 100% to plus 100%.

Figure 8.16 clarifies the relations between directional bias and dynamic bias.

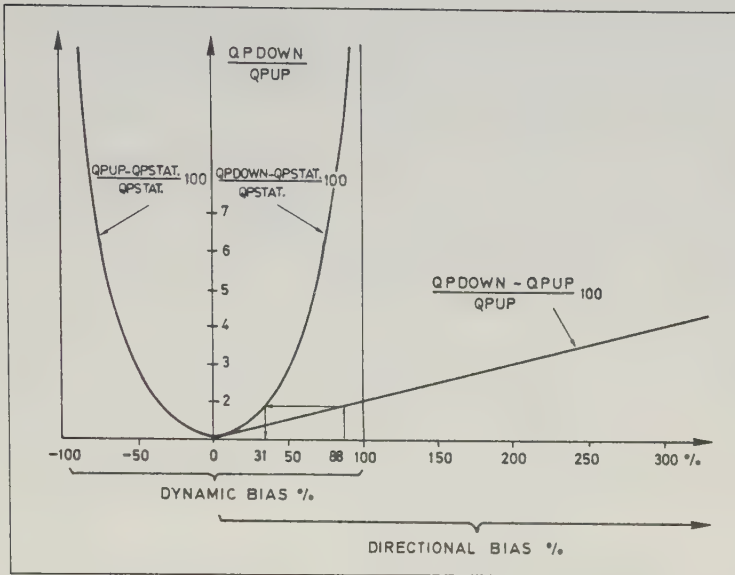


Figure 8.16 Relationship between directional bias and dynamic bias according to the definition

We assume that stationary storms yield the same peak flow as storms moving at a right angle to the direction of conduits. The observed maximal directional bias of 88% in relation to upstream storm movement will be equal to a maximal dynamic bias of 31% in relation to stationary storms (see Figure 8.16). We are also assuming that the dynamic bias for storm movement directions whose orientation in relation to the conduits varies from a parallel direction to a right-angle direction will decrease from the maximal value according to the cosine function:

$$\text{DYNAMIC BIAS } (\phi) = \text{MAX DYNAMIC BIAS } \cos \phi$$

where:

DYNAMIC BIAS (ϕ) is the dynamic bias for storm movement directions that are not parallel to the conduit direction.

MAX DYNAMIC BIAS is maximal dynamic bias, observed for storm movement direction downstream, parallel to the conduit direction

ϕ is an angle between the storm movement direction and the conduit direction.

Figure 8.17 shows the distribution of dynamic bias on different directions and lists the relative probabilities of storm velocity (V) and direction (D).

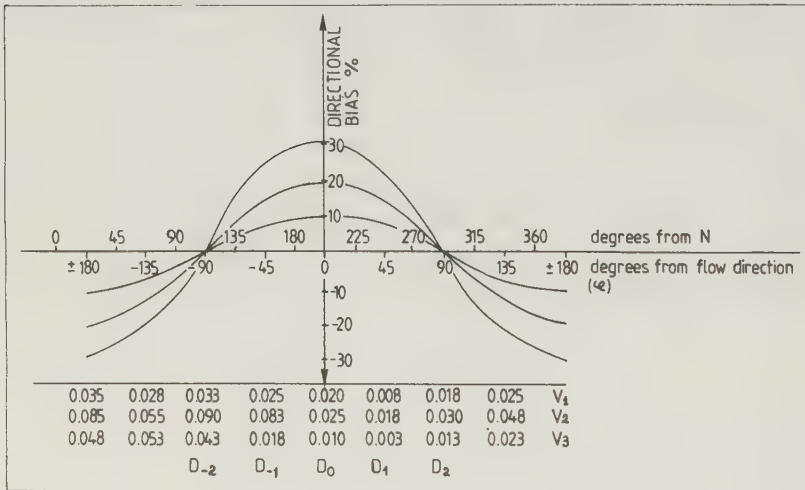


Figure 8.17 Dynamic bias on different directions

Now we can calculate the maximum possible values of dynamic bias for each sector of storm movement direction and each storm velocity interval listed in Table 8.3. By summation of the probabilities for positive bias values exceeding 0, 10 and 20%, the exceedance probabilities for dynamic bias on differently oriented catchments have been calculated.

We define the probabilities shown in Table 3 as follows:

$P(V_i, D_j)$ where: V_i is a velocity interval with $i = 1, 2, 3$

$$V_1 = [0.0, 5.4] \text{ m/s}$$

$$V_2 = [5.5, 12.4] \text{ m/s}$$

$$V_3 = [12.4, 17.4] \text{ m/s}$$

D_j is a 45-degree sector with $j = -2, -1, 0, 1, 2$

$$D-2 = [-112.5, -67.5] \text{ degrees}$$

$$D-1 = [-67.6, -22.5] \text{ degrees}$$

$$D 0 = [-22.4, 22.5] \text{ degrees}$$

$$D 1 = [22.4, 67.5] \text{ degrees}$$

$$D 2 = [67.4, 112.5] \text{ degrees}$$

The calculation of exceedance probabilities was performed by means of the following summations:

$$P(\text{DYNAMIC BIAS} > 0) = \sum_{i=1}^3 \sum_{j=-2}^2 P(V_i, D_j)$$

$$P(\text{DYNAMIC BIAS} > 10) = \sum_{i=1}^2 \sum_{j=-1}^1 P(V_i, D_j)$$

$$P(\text{DYNAMIC BIAS} > 20) = \sum_{j=-1}^1 P(V_1, D_j)$$

$$P(\text{DYNAMIC BIAS} > 30) = 0 \text{ (according to simulations)}$$

By rotating the coordinate system for conduit direction, the summation was repeated in respect to 8 catchment orientations. Figure 8.18 shows the exceedance probabilities for dynamic bias on differently oriented catchments with directional sectors as a curve parameter. Figure 8.19 presents the same values with dynamic bias as a curve parameter. While performing summations of probabilities in the way described above, we have made a very conservative assumption that storms with an intensity and a duration which give the maximum observed dynamic bias have an equal probability of occurrence in all the directional sectors involved in the summations. This assumption is probably not valid; conse-

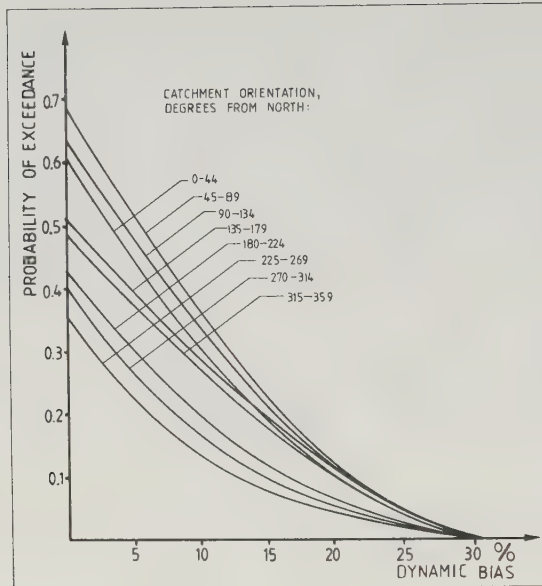
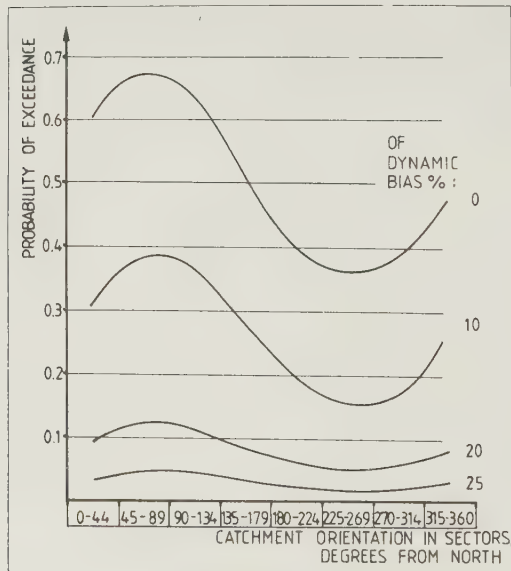


Figure 8.18 Probabilities that the dynamic bias exceeds the value given by the abscissa



Figur 8.19 Probabilities that certain values of the dynamic bias will be exceeded on differently oriented catchments

quently, real exceedance probabilities for dynamic bias are probably much lower than those presented in Figure 8.18.

From Figures 8.18 - 8.19 and Table 8.3 it can be seen that catchments oriented towards the north-east (the 45 - 90 degrees sector) have the highest probability of high dynamic bias. This is a reasonable expectation, since summer storms with high intensity, short duration, and low velocity often move in this direction.

8.7 Conclusions

1. The influence of storm movement on runoff hydrographs has been shown, and the magnitude of the influence has been quantified and presented in statistical terms.
2. Theoretically, the maximal directional bias can reach values of several hundred percent. This can only be shown on conceptual catchments, with specially designed geometry, for storms with short duration, and it is without practical importance.
3. The maximal directional bias shown for real catchments is much smaller than for the conceptual catchment, but it can still reach a significant value.

Maximal directional bias simulated for the Lund catchment is 88 percent in relation to upstream storm movement, or 31 percent in relation to stationary storms following intensity-duration-frequency curves. In the case of catchment No 5 in Lund, the maximal bias was observed with a rainfall duration of 10 minutes and a return period of 1 year.

4. The maximal directional bias occurs with rainfalls whose velocities equal the average flow velocity in the conduits. The average flow velocity on Lund catchments is much smaller than the average storm velocity. Rainfalls with a velocity equal to the flow velocity have a small probability of occurrence.

5. For rainfalls with intensities following the intensity-duration-frequency relationships, the maximal directional bias will occur at durations approximately equal to $1/5$ to $1/3$ of the concentration time for the catchment.
6. Long catchments with straight conduits which run approximately parallel to the long axis of the catchment will show a higher directional bias than catchments with a more complicated sewer geometry.
7. The magnitude of exceedance probability with regard to the dynamic bias values shown in Figure 8.18 - 8.19 suggests that the error in simulated runoff peak discharge which is caused by using stationary storms as input will not be very important from a practical point of view. Still, the phenomenon of directional bias can be one of the reasons why the frequency of rainfall does not follow the frequency of runoff.

9. GENERAL CONCLUSIONS AND DISCUSSION

9. GENERAL CONCLUSIONS AND DISCUSSION

On the basis of rainfall data gathered in 12 gauges in Lund, it was shown that both the areal and the dynamic properties of rainfall influence the shape of the runoff hydrograph and the peak flow discharge.

It was shown that areal rainfall is statistically different from point rainfall. The probability of occurrence of a certain rainfall intensity as an areal value is lower than the respective probability of the same intensity occurring as a point value.

Information about storm velocity and direction does exist in a set of point rainfall data from a sufficiently dense network of gauges. This information can be derived from the data by a relatively simple procedure.

Rainfall movement characteristics can be used to judge which catchments are most exposed to the effect of directional bias. Catchments oriented along the most frequent storm movement direction can expect higher peak flow discharge in comparison with catchments oriented in other directions.

The given probability that certain values of directional bias will be exceeded suggests that the error in simulated peak discharge which arises when stationary storms are used as an input will not be very important from a practical point of view. Rainfalls with movement parameters which yield maximal values with regard to directional bias have a low probability of occurrence.

If the areal and dynamic properties of rain are taken into account when rainfall input is selected the accuracy of the simulated runoff, will be improved.

As was stated at the very beginning of this work, the statistical calculations performed on rainfall data will reduce the amount of information included in the original record. The best results in runoff simulations would be achieved if full series of rainfall data, observed in a dense network of gauges, could be used as an input.

A special method of deriving runoff statistics, referred to as the "staged approach", has recently been developed in Denmark (Harremoës et al 1983). The whole available rainfall series is run through a runoff model, and statistical operations aiming to assess the return period of runoff occurrences are performed on the simulated runoff series. This method would be excellent, provided that areal rainfall with preserved dynamic properties is used as an input, and provided that the runoff model can handle all non-linearities in catchment response. This solution is, of course, of academic interest only, as very few catchments are equipped with a sufficiently dense network of gauges, and because the costs involved in such simulations would be immense. Bearing this in mind, we should perhaps not give up the idea of design storms, completely, but develop a new generation of such storms which would be based on areal rainfall, preserving rainfall movement.

The results presented here can be put to use in developing such area-sensitive, directionally-oriented, and moving design storms. The areal properties of rainfall are expressed in the presented intensity-duration-frequency relationships. These relationships can be employed in developing any traditional design storm, instead of using one-point relationships. Alternatively, the area reduction factors presented in this study can be used in reducing traditional one-point i-d-f relationships to areal values.

The areal i-d-f curves and areal reduction factors contained in this work are only valid for the city of Lund. The question how far these results can be extended beyond Lund has not been answered yet. For example, can we use these relationships in the city of Copenhagen? Some indications about the regional validity of areal reduction factors can be obtained from studies performed by Lindholm in the Oslo region in Norway (Lindholm 1983). The methodology used in Lund for developing areal i-d-f curves was repeated in this region, the investigation being based on records from nine rain-gauges covering an area of about 20 sq. kms. The areal reduction factors derived in Oslo are approximately twice as

large as those presented for Lund. An explanation can be found in the specific geographic and climatic situation of the Oslo region, with high altitude differences within the catchment. When more such studies have been performed, it will be possible to explain regional differences; this in turn, will make the choice of suitable areal reduction factors easier.

The dynamic properties of rainfall can be taken into account by allowing for the movement of the design storms across the catchment. Most of the rainfall-runoff models allow for a number of hyetographs being used as an input. Instead of using the same stationary design storms on all subcatchments, the storm movement can be simulated by assessing lagged hyetographs pertaining to different subcatchments in a sequence reflecting the storm direction, the time lag being chosen in such a way that the required storm velocity is simulated.

The rainfall movement statistics that are presented here are only valid for the city of Lund. Again, the question of regional validity has not been answered yet. There are only a few locations where the statistics of rainfall movement are known. Instead, however, we can use 700 mb wind data - measured at most airports - for calculating the required distribution of storm velocity and direction.

All these solutions are only temporary approximations which provide an opportunity of improving the rainfall input to runoff simulation models used for practical applications. The most desirable - indeed, the final - solution is to develop a statistical rainfall model generating areal rainfall series for any catchment size and orientation. Studies aiming at developing such a model are currently going on in Lund. These studies, however, extend beyond the scope of this thesis.

Among all the hydrological processes, the rainfall process is the most variable one in time and space. The rainfall process is also the most difficult one to analyze and to predict. There are still a great number of basic questions which have to be answered before the nature of the rainfall

process can be better understood. In addition, many further problems must be solved before fully reliable methods of choosing rainfall input for runoff modeling can be developed. The only way of increasing the knowledge about the rainfall process is by means of continued studies, analyzing already available data and starting new measurements. Newly-developed techniques of remote sensing, such as weather radar and satellite observations, will probably gain more importance in these studies.

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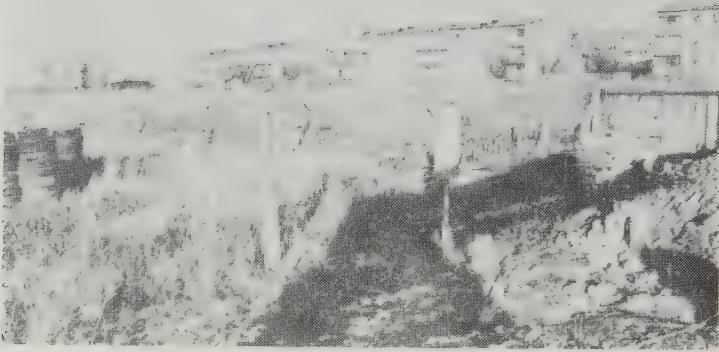
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APPENDIX 1

Fotographs of 12 Raingauges in the City of Lund



Raingauge 1



Raingauge 2



Raingauge 3



Raingauge 4



Raingauge 5



Raingauge 6



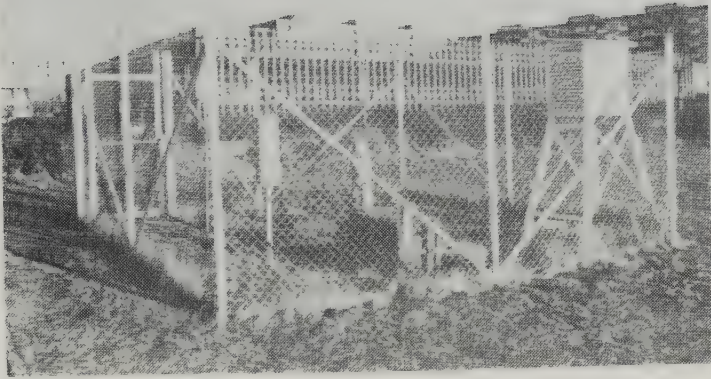
Raingauge 7



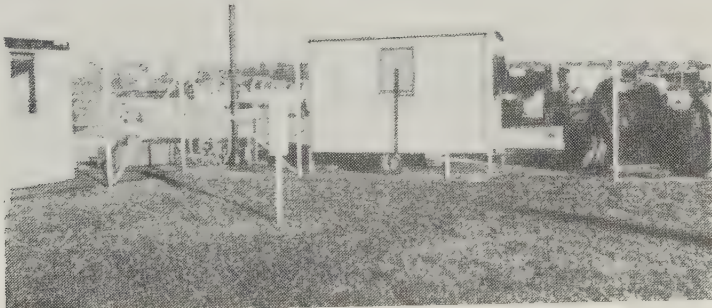
Raingauge 8



Raingauge 9



Raingauge 10



Raingauge 11



Raingauge 12

APPENDIX 2

List of 1-Minute Rainfall Intensities
for 10 Extreme Rainfall Events in Lund

RAINFALL INTENSITY mm/min.

RAINFALL EVENT No1.

RAINGAUGE No:

DATE	TIME	1	2	3	4	5	6	7	8	9	10	11	12
800823	10.04	0.293	0.153	0.077	0.144			0.032	0.104		0.039	0.450	0.141
800823	10.05	0.217	0.352	0.077	0.107			0.032	0.141		0.079	0.450	0.069
800823	10.06	0.105	0.312	0.077	0.107			0.032	0.104		0.039	0.325	0.034
800823	10.07	0.069	0.352	0.038	0.071			0.102	0.068		0.039	0.120	0.069
800823	10.08	0.069	0.272	0.077	0.071			0.137	0.068		0.039	0.160	0.034
800823	10.09	0.069	0.075	0.077	0.035			0.322	0.068		0.039	0.079	0.034
800823	10.10	0.033	0.075	0.077	0.071			0.627	0.068		0.000	0.079	0.069
800823	10.11	0.069	0.037	0.077	0.071			0.512	0.068		0.039	0.039	0.105
800823	10.12	0.069	0.037	0.077	0.071			0.550	0.104		0.039	0.079	0.069
800823	10.13	0.069	0.037	0.077	0.144			0.589	0.104		0.079	0.039	0.105
800823	10.14	0.033	0.037	0.038	0.107			0.322	0.104		0.079	0.120	0.069
800823	10.15	0.069	0.037	0.117	0.144			0.137	0.104		0.079	0.120	0.069
800823	10.16	0.105	0.037	0.198	0.071			0.066	0.104		0.079	0.079	0.069
800823	10.17	0.142	0.075	0.239	0.071			0.066	0.254		0.039	0.079	0.034
800823	10.18	0.179	0.037	0.239	0.071			0.032	0.447		0.119	0.079	0.214
800823	10.19	0.217	0.037	0.117	0.107			0.066	0.330		0.079	0.079	0.287
800823	10.20	0.179	0.075	0.198	0.333			0.066	0.216		0.079	0.039	0.361
800823	10.21	0.179	0.153	0.239	0.219			0.102	0.178		0.079	0.120	0.214
800823	10.22	0.179	0.153	0.239	0.182			0.066	0.216		0.159	0.160	0.105
800823	10.23	0.142	0.114	0.117	0.295			0.066	0.292		0.363	0.284	0.214
800823	10.24	0.142	0.114	0.198	0.257			0.102	0.178		0.486	0.243	0.250
800823	10.25	0.179	0.114	0.157	0.182			0.174	0.216		0.159	0.201	0.214
800823	10.26	0.331	0.232	0.117	0.219			0.210	0.104		0.363	0.160	0.105
800823	10.27	0.447	0.192	0.077	0.144			0.247	0.033		0.159	0.160	0.034
800823	10.28	0.217	0.075	0.038	0.071			0.174	0.141		0.119	0.120	0.069
800823	10.29	0.142	0.075	0.077	0.035			0.137	0.178		0.199	0.201	0.000
800823	10.30	0.105	0.153	0.038	0.144			0.102	0.104		0.079	0.079	0.034
800823	10.31	0.069	0.114	0.077	0.144			0.210	0.068		0.363	0.039	0.034
800823	10.32	0.105	0.153	0.077	0.182			0.210	0.254		0.159	0.079	0.000
800823	10.33	0.069	0.075	0.038	0.071			0.284	0.104		0.039	0.079	0.069
800823	10.34	0.069	0.037	0.077	0.107			0.247	0.068		0.039	0.079	0.000
800823	10.35	0.033	0.114	0.157	0.071			0.174	0.000		0.079	0.079	0.034
800823	10.36	0.069	0.075	0.117	0.000			0.102	0.068		0.000	0.120	0.000
800823	10.37	0.105	0.075	0.239	0.035			0.102	0.725		0.039	0.243	0.034
800823	10.38	0.142	0.114	0.239	0.144			0.066	0.526		0.000	0.079	0.000
800823	10.39	0.408	0.114	0.446	0.371			0.066	0.447		0.000	0.000	0.000
800823	10.40	0.331	0.153	1.080	0.525			0.066	0.408		0.000	0.079	0.000
800823	10.41	0.643	0.153	1.123	0.641			0.102	0.254		0.000	0.408	0.000
800823	10.42	1.001	0.678	0.909	0.525			0.284	0.033		0.000	0.492	0.000
800823	10.43	1.001	1.092	1.509	0.107			0.705	0.033		0.000	0.450	0.000
800823	10.44	0.881	1.384	1.165	0.035			0.744	0.000		0.000	0.408	0.000
800823	10.45	1.001	1.594	0.867	0.000			1.138	0.033		0.000	0.079	0.034
800823	10.46	1.082	1.552	1.466	0.035			1.258	0.104		0.000	0.039	0.000
800823	10.47	0.881	1.342	1.639	0.071			1.580	0.369		0.000	0.000	0.000
800823	10.48	1.163	1.092	0.198	0.371			1.580	0.605		0.000	0.000	0.000
800823	10.49	0.643	0.926	0.198	0.564			0.822	0.526		0.000	0.120	0.000
800823	10.50	0.293	0.843	0.157	0.486			0.666	1.378		0.000	0.367	0.000
800823	10.51	0.408	0.232	0.280	0.564			0.550	1.130		0.000	0.660	0.000
800823	10.52	0.255	0.114	0.198	0.680			0.783	0.565		0.000	0.450	0.000
800823	10.53	0.293	0.075	0.239	0.525			0.705	0.765		0.000	0.243	0.034
800823	10.54	0.105	0.075	0.157	0.486			0.550	0.605		0.000	0.160	0.105
800823	10.55	0.217	0.075	0.117	0.486			0.550	0.330		0.000	0.160	0.361
800823	10.56	0.105	0.075	0.198	0.409			0.550	0.254		0.000	0.201	0.472
800823	10.57	0.142	0.037	0.077	0.333			0.174	0.486		0.000	0.325	0.069
800823	10.58	0.069	0.075	0.077	0.333			0.066	0.292		0.000	0.492	0.000
800823	10.59	0.033	0.114	0.038	0.448			0.066	0.369		0.000	0.744	0.034
800823	11.00	0.069	0.075	0.038	0.371			0.066	0.565		0.000	0.618	0.034
800823	11.01	0.069	0.075	0.000	0.409			0.066	0.846		0.000	0.367	0.034
800823	11.02	0.033	0.075	0.038	0.371			0.066	0.369		0.000	0.576	0.034
800823	11.03	0.000	0.037	0.117	0.371			0.066	0.104		0.000	0.408	0.069

RAINFALL INTENSITY mm/min.

RAINFALL EVENT No 2.

RAINGAUGE No :

DATE	TIME	1	2	3	4	5	6	7	8	9	10	11	12
800709	07.19	0.069	0.037	0.037	0.298			0.066	0.526			0.107	0.248
800709	07.20	0.069	0.037	0.000	0.222			0.102	0.288			0.107	0.441
800709	07.21	0.069	0.000	0.037	0.109			0.102	0.326			0.181	0.280
800709	07.22	0.033	0.037	0.000	0.109			0.066	0.176			0.144	0.122
800709	07.23	0.033	0.075	0.037	0.146			0.032	0.103			0.071	0.185
800709	07.24	0.067	0.075	0.000	0.146			0.032	0.139			0.071	0.091
800709	07.25	0.033	0.153	0.037	0.109			0.066	0.103			0.035	0.091
800709	07.26	0.067	0.153	0.000	0.146			0.066	0.139			0.071	0.091
800709	07.27	0.142	0.037	0.037	0.109			0.032	0.176			0.035	0.060
800709	07.28	0.142	0.075	0.000	0.071			0.066	0.139			0.035	0.029
800709	07.29	0.069	0.037	0.037	0.035			0.032	0.067			0.071	0.060
800709	07.30	0.033	0.075	0.000	0.035			0.066	0.103			0.071	0.060
800709	07.31	0.069	0.075	0.037	0.035			0.066	0.032			0.071	0.029
800709	07.32	0.069	0.075	0.037	0.109			0.032	0.032			0.000	0.029
800709	07.33	0.069	0.000	0.000	0.109			0.066	0.103			0.035	0.060
800709	07.34	0.033	0.000	0.000	0.109			0.102	0.250			0.000	0.060
800709	07.35	0.069	0.037	0.037	0.035			0.032	0.103			0.035	0.029
800709	07.36	0.000	0.000	0.037	0.000			0.032	0.067			0.000	0.029
800709	07.37	0.033	0.037	0.000	0.035			0.066	0.032			0.071	0.000
800709	07.38	0.033	0.037	0.000	0.000			0.032	0.032			0.035	0.000
800709	07.39	0.000	0.037	0.037	0.071			0.066	0.067			0.035	0.029
800709	07.40	0.033	0.075	0.037	0.035			0.032	0.032			0.000	0.029
800709	07.41	0.033	0.037	0.000	0.035			0.066	0.067			0.255	0.029
800709	07.42	0.033	0.114	0.037	0.035			0.102	0.067			0.255	0.000
800709	07.43	0.033	0.075	0.155	0.035			0.210	0.032			0.181	0.029
800709	07.44	0.000	0.075	0.037	0.109			0.512	0.032			0.107	0.000
800709	07.45	0.033	0.037	0.195	0.109			0.435	0.067			0.144	0.029
800709	07.46	0.179	0.114	0.000	0.109			0.284	0.067			0.144	0.029
800709	07.47	0.179	0.114	0.000	0.071			0.359	0.103			0.144	0.091
800709	07.48	0.179	0.192	0.000	0.035			0.359	0.103			0.107	0.060
800709	07.49	0.179	0.192	0.000	0.071			0.783	0.087			0.107	0.153
800709	07.50	0.293	0.312	0.000	0.109			1.298	0.176			0.144	0.216
800709	07.51	0.293	0.514	0.000	0.260			1.338	0.139			0.071	0.185
800709	07.52	0.486	0.596	0.000	0.222			0.783	0.213			0.071	0.060
800709	07.53	0.370	0.637	0.000	0.109			1.256	0.213			0.035	0.060
800709	07.54	0.293	0.637	0.000	0.109			1.218	0.103			0.035	0.029
800709	07.55	0.217	0.843	0.000	0.109			0.822	0.139			0.035	0.029
800709	07.56	0.142	0.760	0.000	0.071			0.822	0.067			0.035	0.029
800709	07.57	0.105	0.884	0.000	0.035			0.744	0.032			0.107	0.000
800709	07.58	0.217	0.514	0.000	0.035			0.960	0.032			0.071	0.029
800709	07.59	0.293	0.514	0.000	0.035			0.901	0.032			0.329	0.091
800709	08.00	0.217	0.474	0.000	0.071			0.550	0.032			0.517	0.060
800709	08.01	0.105	0.433	0.000	0.109			0.627	0.032			0.292	0.029
800709	08.02	0.682	0.393	0.000	0.071			0.473	0.139			0.329	0.060
800709	08.03	0.525	0.474	0.000	0.688			0.174	0.067			0.441	0.060
800709	08.04	0.408	0.433	0.000	1.405			0.066	0.067			0.705	0.153
800709	08.05	0.331	0.433	0.000	0.649			0.000	1.358			0.517	0.312
800709	08.06	0.447	0.153	0.000	0.531			0.000	1.236			0.441	0.344
800709	08.07	0.255	0.153	0.000	0.609			0.000	0.715			1.124	0.505
800709	08.08	0.293	0.037	0.000	0.260			0.000	0.636			1.239	0.538
800709	08.09	0.217	0.037	0.000	0.492			0.032	0.402			1.354	0.441
800709	08.10	0.408	0.000	0.000	0.965			0.000	0.250			0.705	0.376
800709	08.11	0.447	0.000	0.000	1.045			0.000	0.480			0.329	1.095
800709	08.12	0.682	0.000	0.000	1.769			0.000	1.236			0.292	0.963
800709	08.13	0.525	0.000	0.000	0.965			0.000	1.358			0.071	1.460
800709	08.14	0.069	0.000	0.000	0.337			0.000	<u>2.310</u>			0.035	1.626
800709	08.15	0.000	0.000	0.000	0.146			0.000	1.604			0.000	0.570
800709	08.16	0.033	0.037	0.000	0.071			0.000	0.288			0.000	0.122
800709	08.17	0.000	0.000	0.000	0.000			0.000	0.139			0.000	0.216
800709	08.18	0.000	0.000	0.000	0.035			0.000	0.103			0.000	0.185

RAINFALL INTENSITY mm/min.

RAINFALL EVENT No 3.

RAINGAUGE No :

DATE TIME

1 2 3 4 5 6 7 8 9 10 11 12

800713 10.47	0.000	0.000	0.000	0.107	0.000		0.000	0.000	0.119	0.039	0.069	
800713 10.48	0.000	0.037	0.000	0.107	0.035		0.068	0.000	0.079	0.160	0.069	
800713 10.49	0.033	0.000	0.000	0.107	0.035		0.033	0.000	0.404	0.120	0.105	
800713 10.50	0.033	0.000	0.000	0.071	0.072		0.068	0.000	0.322	0.492	0.069	
800713 10.51	0.033	0.000	0.000	0.000	0.108		0.141	0.032	0.776	0.660	0.034	
800713 10.52	0.217	0.000	0.000	0.035	0.182		0.068	0.000	0.734	0.744	0.034	
800713 10.53	0.217	0.000	0.038	0.219	0.182		0.033	0.032	0.527	1.551	0.105	
800713 10.54	0.370	0.000	0.117	0.719	0.295		0.000	0.032	0.486	0.618	0.214	
800713 10.55	0.142	0.075	0.077	0.525	0.445		0.141	0.100	0.281	0.997	0.287	
800713 10.56	0.486	0.037	0.038	0.448	0.635		0.408	0.135	0.199	0.576	0.398	
800713 10.57	0.486	0.037	0.198	1.748	0.750		0.408	0.391	0.445	0.492	0.398	
800713 10.58	0.762	0.037	0.446	1.151	0.559		0.447	0.579	0.404	0.618	0.509	
800713 10.59	0.486	0.037	0.867	1.230	0.257		0.330	0.280	0.322	1.551	0.547	
800713 11.00	0.142	0.000	0.404	1.072	0.408		0.805	0.243	0.322	0.997	0.398	
800713 11.01	0.142	0.037	0.529	0.602	0.408		0.725	0.428	0.445	0.534	0.324	
800713 11.02	0.069	0.000	0.198	1.072	0.257		0.805	0.655	0.240	0.325	0.177	
800713 11.03	0.105	0.037	0.117	1.270	0.182		0.486	0.693	0.079	0.243	0.622	
800713 11.04	0.069	0.000	0.038	0.758	0.220		0.526	0.428	0.159	0.160	0.697	
800713 11.05	0.105	0.000	0.038	0.448	0.295		0.645	0.391	0.240	0.120	0.435	
800713 11.06	0.217	0.114	0.038	0.333	0.295		0.725	0.317	0.199	0.120	0.250	
800713 11.07	0.255	0.114	0.038	0.371	0.559		0.605	0.428	0.240	0.243	0.287	
800713 11.08	0.142	0.037	0.038	0.295	0.370		0.178	0.280	0.486	0.408	0.324	
800713 11.09	0.105	0.037	0.077	0.219	0.332		0.369	0.207	0.486	0.492	0.361	
800713 11.10	0.105	0.037	0.363	0.144	0.220		0.292	0.428	0.159	0.576	0.398	
800713 11.11	0.069	0.114	0.363	0.182	0.220		0.141	0.579	0.199	0.618	0.250	
800713 11.12	0.000	0.272	0.198	0.409	0.332		0.141	0.617	0.079	0.744	0.250	
800713 11.13	0.069	0.312	0.157	0.448	0.445		0.104	0.317	0.119	0.367	0.287	
800713 11.14	0.105	0.555	0.117	0.602	0.408		0.104	0.171	0.079	0.284	0.177	
800713 11.15	0.255	0.843	0.117	0.680	0.145		0.254	0.066	0.079	0.243	0.177	
800713 11.16	0.486	1.300	0.077	0.295	0.072		0.565	0.066	0.079	0.201	0.177	
800713 11.17	0.525	1.300	0.239	0.409	0.072		0.526	0.135	0.039	0.039	0.214	
800713 11.18	0.841	0.760	0.363	0.371	0.072		0.292	0.066	0.079	0.039	0.214	
800713 11.19	0.682	0.760	0.446	0.257	0.108		0.292	0.135	0.039	0.000	0.472	
800713 11.20	0.801	0.637	0.655	0.219	0.072		0.254	0.317	0.039	0.000	0.398	
800713 11.21	0.881	0.596	0.613	0.107	0.072		0.254	0.243	0.039	0.000	0.250	
800713 11.22	0.255	0.433	0.613	0.071	0.072		0.292	0.354	0.039	0.000	0.105	
800713 11.23	0.142	0.192	0.655	0.035	0.072		0.141	0.354	0.000	0.000	0.034	
800713 11.24	0.525	0.037	0.404	0.000	0.035		0.068	0.171	0.000	0.000	0.034	
800713 11.25	0.641	0.000	0.198	0.000	0.035		0.033	0.171	0.039	0.039	0.000	
800713 11.26	0.331	0.037	0.404	0.000	0.035		0.000	0.135	0.000	0.000	0.034	
800713 11.27	0.069	0.000	0.782	0.000	0.035		0.000	0.135	0.000	0.000	0.000	
800713 11.28	0.033	0.000	0.487	0.000	0.000		0.000	0.066	0.000	0.000	0.000	
800713 11.29	0.000	0.000	0.404	0.000	0.035		0.033	0.000	0.000	0.000	0.000	
800713 11.30	0.000	0.000	0.000	0.035	0.000		0.000	0.032	0.000	0.000	0.034	
800713 11.31	0.000	0.000	0.077	0.000	0.000		0.000	0.000	0.000	0.000	0.000	
800713 11.32	0.000	0.000	0.038	0.000	0.000		0.000	0.000	0.000	0.000	0.000	
800713 11.33	0.033	0.000	0.038	0.000	0.035		0.000	0.032	0.000	0.000	0.000	
800713 11.38	0.000	0.077	0.000	0.000	0.000		0.000	0.032	0.000	0.039	0.000	
800713 12.11	0.000	0.035	0.038	0.000	0.000		0.000	0.000	0.000	0.000	0.000	
800713 12.21	0.000	0.000	0.000	0.000	0.000		0.000	0.000	0.039	0.039	0.000	
800713 12.24	0.000	0.037	0.000	0.000	0.000		0.000	0.000	0.000	0.000	0.000	
800713 12.27	0.000	0.077	0.000	0.000	0.000		0.000	0.000	0.000	0.000	0.000	
800713 12.28	0.000	0.037	0.000	0.000	0.000		0.000	0.000	0.000	0.000	0.000	
800713 12.29	0.000	0.075	0.000	0.000	0.000		0.000	0.000	0.000	0.000	0.000	
800713 12.30	0.033	0.000	0.035	0.000	0.000		0.000	0.000	0.000	0.000	0.000	
800713 12.31	0.000	0.077	0.000	0.000	0.000		0.000	0.000	0.000	0.000	0.000	
800713 12.32	0.033	0.037	0.077	0.000	0.000		0.000	0.000	0.000	0.000	0.000	
800713 12.34	0.077	0.000	0.038	0.000	0.000		0.000	0.000	0.000	0.000	0.000	
800713 12.35	0.033	0.037	0.038	0.000	0.000		0.000	0.000	0.000	0.079	0.000	
800713 12.36	0.077	0.000	0.038	0.000	0.000		0.000	0.000	0.000	0.000	0.000	

RAINFALL INTENSITY mm/min.

RAINFALL EVENT No 4.

RAINGAUGE NO :

DATE	TIME	1	2	3	4	5	6	7	8	9	10	11	12
800823	11.04	0.033	0.037	0.198	0.144			0.032	0.000		0.000	0.534	0.000
800823	11.05	0.331	0.037	0.198	0.035			0.066	0.068		0.000	0.534	0.034
800823	11.06	0.255	0.075	0.280	0.035			0.137	0.000		0.000	0.284	0.000
800823	11.07	0.217	0.153	0.117	0.035			0.066	0.000		0.000	0.039	0.000
800823	11.08	0.331	0.232	0.038	0.000			0.032	0.033		0.000	0.039	0.034
800823	11.09	0.142	0.114	0.038	0.035			0.066	0.000		0.000	0.039	0.000
800823	11.10	0.000	0.114	0.000	0.000			0.247	0.000		0.000	0.039	0.000
800823	11.11	0.033	0.037	0.000	0.000			0.174	0.000		0.000	0.000	0.000
800823	11.12	0.000	0.037	0.867	0.000			0.102	0.000		0.000	0.039	0.000
800823	11.13	0.069	0.000	1.639	0.000			0.102	0.000		0.000	0.000	0.000
800823	11.14	0.486	0.037	2.247	0.000			0.032	0.104		0.000	0.000	0.000
800823	11.15	0.682	0.153	1.337	0.000			0.000	0.369		0.000	0.000	0.000
800823	11.16	1.406	0.596	0.909	0.071			0.032	0.330		0.000	0.000	0.000
800823	11.17	1.940	0.433	1.037	0.219			0.032	0.254		0.000	0.000	0.000
800823	11.18	1.163	0.192	0.655	0.295			0.247	0.141		0.000	0.000	0.000
800823	11.19	1.082	0.153	0.321	0.219			0.744	0.068		0.000	0.039	0.000
800823	11.20	0.486	0.312	0.404	0.107			1.459	0.033		0.000	0.160	0.000
800823	11.21	0.447	0.393	0.198	0.071			0.901	0.033		0.000	0.284	0.000
800823	11.22	0.142	0.153	0.038	0.035			0.627	0.000		0.000	0.284	0.000
800823	11.23	0.069	0.153	0.000	0.035			0.247	0.033		0.000	0.120	0.000
800823	11.24	0.033	0.153	0.038	0.000			0.512	0.000		0.000	0.079	0.000
800823	11.25	0.033	0.114	0.000	0.000			0.397	0.000		0.000	0.000	0.034
800823	11.26	0.000	0.232	0.000	0.000			0.137	0.000		0.000	0.039	0.000
800823	11.27	0.000	0.114	0.000	0.000			0.066	0.000		0.000	0.000	0.000
800823	11.28	0.000	0.075	0.038	0.000			0.102	0.000		0.000	0.000	0.000
800823	11.29	0.000	0.037	0.000	0.035			0.066	0.000		0.000	0.000	0.000
800823	11.30	0.000	0.037	0.000	0.000			0.032	0.000		0.000	0.000	0.000
800823	11.31	0.000	0.000	0.000	0.000			0.032	0.033		0.000	0.039	0.000
800823	11.32	0.033	0.000	0.038	0.000			0.000	0.000		0.000	0.000	0.000
800823	11.33	0.000	0.000	0.157	0.035			0.000	0.000		0.000	0.000	0.069
800823	11.34	0.069	0.000	0.404	0.107			0.032	0.033		0.000	0.120	0.105
800823	11.35	0.331	0.000	0.038	0.144			0.000	0.033		0.000	0.120	0.069
800823	11.36	0.293	0.075	0.280	0.107			0.000	0.104		0.000	0.325	0.000
800823	11.37	0.217	0.192	0.867	0.071			0.000	0.292		0.000	0.492	0.034
800823	11.38	0.762	0.114	0.571	0.107			0.032	0.685		0.000	0.534	0.000
800823	11.39	0.841	0.075	0.280	0.182			0.174	0.526		0.000	0.408	0.034
800823	11.40	0.841	0.000	0.077	0.219			0.901	0.141		0.000	0.201	0.361
800823	11.41	0.255	0.272	0.077	0.144			0.705	0.104		0.039	0.039	0.361
800823	11.42	0.142	0.514	0.038	0.107			0.666	0.068		0.039	0.243	0.287
800823	11.43	0.105	0.352	0.000	0.107			0.783	0.033		0.079	0.284	0.214
800823	11.44	0.069	0.153	0.038	0.071			1.019	0.033		0.119	0.160	0.069
800823	11.45	0.033	0.075	0.000	0.071			0.627	0.000		0.079	0.201	0.034
800823	11.46	0.033	0.075	0.038	0.000			0.210	0.033		0.119	0.201	0.034
800823	11.47	0.000	0.037	0.000	0.035			0.102	0.000		0.119	0.160	0.034
800823	11.48	0.033	0.037	0.000	0.000			0.032	0.033		0.159	0.079	0.034
800823	11.49	0.000	0.000	0.038	0.035			0.066	0.000		0.322	0.000	0.000
800823	11.50	0.000	0.037	0.000	0.000			0.032	0.000		0.119	0.000	0.069
800823	11.51	0.000	0.000	0.000	0.000			0.000	0.000		0.119	0.039	0.000
800823	11.52	0.000	0.000	0.000	0.035			0.032	0.000		0.119	0.039	0.000
800823	11.53	0.033	0.037	0.038	0.000			0.000	0.033		0.039	0.000	0.034
800823	11.54	0.000	0.000	0.000	0.000			0.000	0.000		0.039	0.039	0.000
800823	11.56	0.000	0.000	0.000	0.000			0.032	0.000		0.039	0.000	0.034
800823	11.57	0.000	0.000	0.038	0.000			0.000	0.000		0.000	0.039	0.000
800823	11.59	0.000	0.037	0.000	0.035			0.032	0.000		0.000	0.000	0.000
800823	12.00	0.000	0.000	0.000	0.000			0.000	0.033		0.000	0.000	0.000
800823	12.02	0.000	0.000	0.038	0.000			0.000	0.000		0.000	0.000	0.000
800823	12.05	0.000	0.000	0.000	0.000			0.000	0.000		0.039	0.000	0.000
800823	12.06	0.000	0.000	0.038	0.000			0.000	0.000		0.000	0.000	0.000
800823	12.25	0.000	0.000	0.038	0.000			0.000	0.000		0.000	0.000	0.000
800823	12.27	0.000	0.037	0.000	0.000			0.000	0.000		0.000	0.000	0.000
800823	12.28	0.000	0.433	0.000	0.000			0.000	0.000		0.000	0.000	0.000

RAINFALL INTENSITY mm/min.

RAINFALL EVENT No 5.

RAINGAUGE No :

DATE	TIME	1	2	3	4	5	6	7	8	9	10	11	12
790524	15.59	0.000	0.000		0.000		0.000	0.000	0.178	0.000	0.000	0.079	0.177
790524	16.00	0.036	0.000		0.000		0.072	0.000	0.330	0.000	0.039	0.120	0.214
790524	16.01	0.150	0.033		0.000		0.072	0.000	0.292	0.000	0.039	0.079	0.141
790524	16.02	0.150	0.033		0.000		0.072	0.137	0.178	0.066	0.000	0.039	0.105
790524	16.03	0.150	0.105		0.000		0.145	0.473	0.068	0.135	0.119	0.120	0.105
790524	16.04	0.073	0.331		0.000		0.145	0.174	0.068	0.207	0.199	0.284	0.141
790524	16.05	0.073	0.921		0.117		0.035	0.102	0.178	0.354	0.240	0.243	0.250
790524	16.06	0.073	0.722		0.446		0.072	0.137	0.141	0.280	0.240	0.201	0.250
790524	16.07	0.112	0.525		0.867		0.108	0.137	0.178	0.207	0.404	0.243	0.214
790524	16.08	0.190	0.408		1.466		0.145	0.247	0.216	0.100	0.199	0.243	0.324
790524	16.09	0.150	0.331		1.208		0.182	0.512	0.178	0.207	0.119	0.284	0.361
790524	16.10	0.073	0.217		0.782		0.220	0.473	0.254	0.391	0.119	0.284	0.250
790524	16.11	0.112	0.408		0.404		0.108	0.359	0.254	0.207	0.079	0.618	0.214
790524	16.12	0.073	0.525		0.363		0.108	0.247	0.178	0.207	0.039	0.534	0.361
790524	16.13	0.112	0.486		0.404		0.072	0.137	0.068	0.280	0.119	0.284	0.361
790524	16.14	0.190	0.486		0.613		0.072	0.102	0.216	0.317	0.079	0.243	0.287
790524	16.15	0.229	0.408		0.655		0.035	0.032	0.330	0.171	0.079	0.079	0.177
790524	16.16	0.190	0.255		0.487		0.035	0.032	0.292	0.171	0.039	0.079	0.105
790524	16.17	0.112	0.142		0.280		0.072	0.032	0.178	0.207	0.039	0.039	0.069
790524	16.18	0.112	0.105		0.239		0.072	0.032	0.104	0.171	0.000	0.039	0.069
790524	16.19	0.036	0.033		0.198		0.035	0.032	0.068	0.135	0.039	0.000	0.034
790524	16.20	0.036	0.033		0.077		0.035	0.032	0.033	0.100	0.000	0.000	0.034
790524	16.21	0.036	0.033		0.077		0.035	0.000	0.000	0.100	0.000	0.000	0.000
790524	16.22	0.036	0.033		0.038		0.035	0.066	0.033	0.032	0.039	0.039	0.000
790524	16.23	0.036	0.000		0.000		0.000	0.066	0.000	0.032	0.039	0.000	0.034
790524	16.24	0.000	0.033		0.000		0.000	0.066	0.033	0.000	0.039	0.079	0.034
790524	16.25	0.000	0.000		0.038		0.000	0.066	0.000	0.000	0.039	0.120	0.069
790524	16.26	0.000	0.069		0.000		0.035	0.066	0.033	0.032	0.000	0.039	0.034
790524	16.27	0.036	0.069		0.077		0.000	0.066	0.068	0.000	0.000	0.039	0.034
790524	16.28	0.000	0.033		0.038		0.035	0.032	0.100	0.000	0.000	0.000	0.000
790524	16.29	0.000	0.069		0.077		0.000	0.032	0.033	0.032	0.000	0.000	0.000
790524	16.30	0.036	0.033		0.038		0.000	0.000	0.000	0.000	0.000	0.000	0.000
790524	16.31	0.000	0.000		0.038		0.000	0.032	0.000	0.032	0.000	0.039	0.034
790524	16.32	0.000	0.000		0.038		0.000	0.000	0.000	0.000	0.000	0.000	0.000
790524	16.33	0.000	0.000		0.000		0.000	0.000	0.033	0.000	0.000	0.000	0.000
790524	16.37	0.000	0.000		0.000		0.000	0.000	0.000	0.000	0.039	0.000	0.000
790524	18.16	0.000	0.000		0.000		0.000	0.000	0.000	0.000	0.000	0.079	0.000
790524	18.21	0.000	0.000		0.000		0.000	0.000	0.000	0.000	0.000	0.160	0.000
790524	18.29	0.000	0.000		0.000		0.000	0.000	0.000	0.000	0.000	0.120	0.000
790524	21.14	0.000	0.000		0.038		0.000	0.000	0.000	0.000	0.000	0.000	0.000
790524	21.17	0.000	0.000		0.000		0.000	0.000	0.000	0.000	0.039	0.000	0.000
790524	21.18	0.000	0.000		0.000		0.000	0.550	0.000	0.000	0.039	0.120	0.034
790524	21.19	0.000	0.033		0.000		0.035	0.322	0.000	0.000	0.079	0.079	0.069
790524	21.20	0.073	0.370		0.000		0.108	0.174	0.141	0.000	0.119	0.120	0.141
790524	21.21	0.112	0.293		0.239		0.108	0.032	0.141	0.032	0.119	0.039	0.141
790524	21.22	0.150	0.179		0.280		0.108	0.032	0.104	0.171	0.039	0.039	0.069
790524	21.23	0.073	0.069		0.198		0.108	0.032	0.068	0.171	0.000	0.039	0.034
790524	21.24	0.036	0.033		0.077		0.035	0.000	0.033	0.135	0.039	0.000	0.034
790524	21.25	0.036	0.033		0.038		0.035	0.032	0.000	0.032	0.039	0.000	0.000
790524	21.26	0.000	0.000		0.000		0.000	0.000	0.033	0.000	0.000	0.000	0.034
790524	21.27	0.036	0.000		0.000		0.035	0.032	0.000	0.032	0.000	0.039	0.000
790524	21.28	0.000	0.033		0.000		0.035	0.032	0.000	0.000	0.039	0.000	0.034
790524	21.29	0.000	0.000		0.038		0.000	0.000	0.033	0.000	0.000	0.000	0.000
790524	21.30	0.036	0.033		0.038		0.000	0.000	0.000	0.032	0.039	0.000	0.000
790524	21.31	0.000	0.000		0.000		0.035	0.000	0.000	0.000	0.000	0.000	0.000
790524	21.32	0.000	0.000		0.000		0.000	0.032	0.000	0.000	0.000	0.039	0.000
790524	21.33	0.000	0.000		0.000		0.000	0.000	0.033	0.000	0.000	0.000	0.000
790524	21.34	0.000	0.033		0.000		0.000	0.000	0.000	0.032	0.000	0.000	0.034
790524	21.35	0.000	0.000		0.038		0.000	0.000	0.000	0.000	0.000	0.000	0.000
790524	21.36	0.000	0.000		0.000		0.035	0.000	0.000	0.000	0.000	0.000	0.000

RAINFALL EVENT No 6.

RAINGAUGE No :

[illegible]

RAINFALL INTENSITY mm/min.

RAINFALL EVENT No 7.

RAINGAUGE No :

DATE	TIME	1	2	3	4	5	6	7	8	9	10	11	12
800822	22.05	0.000	0.000	0.038	0.000		0.000	0.000		0.000	0.000	0.000	
800822	22.06	0.000	0.272	0.487	0.000		0.000	0.000		0.000	0.000	0.000	
800822	22.07	0.217	1.050	1.037	0.000		0.000	0.000		0.000	0.000	0.000	
800822	22.08	0.881	0.555	0.697	0.000		0.397	0.254		0.000	0.000	0.000	
800822	22.09	0.921	0.719	0.613	0.758		1.059	1.336		0.000	0.000	0.000	
800822	22.10	0.921	0.596	0.198	2.110		1.742	1.336		0.000	0.284	0.547	
800822	22.11	0.331	0.153	0.198	1.389		0.901	0.408		0.281	0.913	0.547	
800822	22.12	0.142	0.075	0.117	0.525		0.744	0.178		0.445	1.125	0.398	
800822	22.13	0.069	0.114	0.077	0.257		0.210	0.178		0.693	0.450	0.214	
800822	22.14	0.069	0.075	0.077	0.219		0.137	0.104		0.693	0.243	0.105	
800822	22.15	0.033	0.075	0.077	0.107		0.137	0.033		0.363	0.160	0.177	
800822	22.16	0.033	0.075	0.038	0.035		0.066	0.033		0.159	0.079	0.034	
800822	22.17	0.033	0.037	0.077	0.035		0.066	0.141		0.159	0.079	0.034	
800822	22.18	0.033	0.037	0.038	0.182		0.066	0.292		0.039	0.000	0.177	
800822	22.19	0.105	0.037	0.377	0.295		0.000	0.178		0.281	0.079	0.177	
800822	22.20	0.142	0.037	0.077	0.257		0.032	0.178		0.281	0.201	0.141	
800822	22.21	0.179	0.075	0.117	0.257		0.066	0.141		0.281	0.201	0.177	
800822	22.22	0.142	0.153	0.446	0.162		0.066	0.141		0.240	0.243	0.324	
800822	22.23	0.370	0.037	0.487	0.219		0.102	0.141		0.159	0.160	0.141	
800822	22.24	0.331	0.114	0.198	0.162		0.102	0.254		0.199	0.160	0.105	
800822	22.25	0.179	0.037	0.157	0.330		0.102	0.447		0.322	0.120	0.141	
800822	22.26	0.142	0.114	0.260	0.602		0.102	0.363		0.240	0.201	0.214	
800822	22.27	0.370	0.075	0.190	0.564		0.102	0.466		0.199	0.367	0.177	
800822	22.28	0.179	0.232	0.196	0.719		0.137	0.565		0.119	0.408	0.141	
800822	22.29	0.142	0.232	0.377	0.602		0.102	0.765		0.159	0.450	0.287	
800822	22.30	0.069	0.075	0.038	0.636		0.455	0.447		0.039	0.576	0.287	
800822	22.31	0.105	0.037	0.030	0.641		0.284	0.254		0.079	0.450	0.324	
800822	22.32	0.033	0.037	0.038	0.257		0.102	0.104		0.199	0.702	0.141	
800822	22.33	0.033	0.000	0.030	0.107		0.032	0.104		0.199	0.534	0.069	
800822	22.34	0.033	0.037	0.038	0.144		0.000	0.178		0.159	0.120	0.141	
800822	22.35	0.000	0.000	0.000	0.219		0.032	0.178		0.199	0.079	0.141	
800822	22.36	0.069	0.037	0.038	0.162		0.000	0.141		0.281	0.120	0.361	
800822	22.37	0.069	0.037	0.077	0.144		0.032	0.141		0.404	0.120	0.214	
800822	22.38	0.069	0.037	0.036	0.162		0.000	0.104		0.240	0.120	0.141	
800822	22.39	0.032	0.037	0.038	0.107		0.032	0.447		0.119	0.120	0.105	
800822	22.40	0.030	0.038	0.000	0.525		0.000	0.665		0.199	0.079	0.584	
800822	22.41	0.069	0.037	0.077	0.650		0.032	0.330		0.119	0.120	0.659	
800822	22.42	0.105	0.000	0.077	0.000		0.032	0.369		0.199	0.367	0.141	
800822	22.43	0.142	0.000	0.000	0.371		0.000	0.447		0.079	0.325	0.214	
800822	22.44	0.069	0.037	0.038	0.123		0.032	0.292		0.000	0.325	0.214	
800822	22.45	0.032	0.000	0.000	0.219		0.032	0.068		0.119	0.284	0.214	
800822	22.46	0.033	0.037	0.077	0.035		0.032	0.033		0.119	0.243	0.177	
800822	22.47	0.000	0.000	0.000	0.000		0.032	0.033		0.119	0.079	0.105	
800822	22.48	0.033	0.000	0.000	0.107		0.000	0.068		0.119	0.039	0.069	
800822	22.49	0.032	0.077	0.038	0.107		0.032	0.033		0.079	0.079	0.069	
800822	22.50	0.033	0.000	0.038	0.371		0.000	0.033		0.039	0.120	0.069	
800822	22.51	0.000	0.037	0.030	0.071		0.032	0.068		0.079	0.120	0.034	
800822	22.52	0.033	0.037	0.038	0.071		0.000	0.033		0.079	0.039	0.034	
800822	22.53	0.033	0.000	0.000	0.035		0.032	0.033		0.039	0.039	0.069	
800822	22.54	0.033	0.037	0.038	0.035		0.032	0.033		0.039	0.079	0.034	
800822	22.55	0.000	0.037	0.038	0.035		0.032	0.000		0.039	0.039	0.034	
800822	22.56	0.033	0.000	0.000	0.035		0.032	0.033		0.039	0.039	0.000	
800822	22.57	0.033	0.037	0.038	0.000		0.000	0.033		0.039	0.039	0.034	
800822	22.58	0.000	0.000	0.038	0.035		0.032	0.033		0.000	0.039	0.034	
800822	22.59	0.032	0.037	0.038	0.035		0.032	0.000		0.039	0.000	0.000	
800822	23.00	0.000	0.000	0.000	0.035		0.000	0.033		0.039	0.039	0.034	
800822	23.01	0.032	0.037	0.038	0.000		0.032	0.000		0.039	0.000	0.034	
800822	23.02	0.033	0.037	0.038	0.035		0.032	0.033		0.000	0.039	0.000	
800822	23.03	0.000	0.000	0.000	0.035		0.000	0.033		0.039	0.000	0.034	
800822	23.04	0.033	0.037	0.038	0.035		0.032	0.033		0.039	0.000	0.000	

RAINFALL INTENSITY mm/min.

RAINFALL EVENT No 8.

RAINGAUGE No :

DATE	TIME	1	2	3	4	5	6	7	8	9	10	11	12
800706	10.54	0.000	0.000	0.037	0.000				0.000		0.000	0.000	
800706	11.43	0.000	0.000	0.000	0.000				0.000		0.035	0.000	
800706	11.49	0.000	0.037	0.000	0.000				0.000		0.000	0.000	
800706	11.50	0.000	0.037	0.000	0.000				0.000		0.000	0.000	
800706	11.51	0.000	0.037	0.000	0.000				0.000		0.000	0.000	
800706	11.53	0.000	0.000	0.000	0.222				0.000		0.181	0.000	
800706	11.54	0.069	0.037	0.000	0.492				0.000		0.107	0.000	
800706	11.55	0.035	0.000	0.000	0.668				0.250		0.255	0.344	
800706	11.56	0.033	0.000	0.000	1.000				0.914		0.592	0.344	
800706	11.57	0.000	0.000	0.000	0.375				0.378		1.009	0.505	
800706	11.58	0.069	0.037	0.000	0.337				0.636		0.781	1.128	
800706	11.59	0.141	0.000	0.000	0.806				0.636		0.933	0.635	
800706	12.00	0.105	0.037	0.000	0.531				0.596		0.441	0.635	
800706	12.01	0.293	0.000	0.000	0.453				0.518		0.404	0.603	
800706	12.02	0.843	0.000	0.000	0.337				0.326		0.517	0.344	
800706	12.03	0.564	0.000	0.000	0.260				0.326		0.366	0.312	
800706	12.04	0.370	0.000	0.000	0.414				0.176		0.144	0.312	
800706	12.05	0.293	0.037	0.000	0.298				0.288		0.107	0.570	
800706	12.06	0.447	0.000	0.037	0.298				0.288		0.071	0.344	
800706	12.07	0.179	0.000	0.037	0.298				0.288		0.035	0.280	
800706	12.08	0.105	0.000	0.000	0.260				0.250		0.071	0.216	
800706	12.09	0.033	0.000	0.037	0.260				0.176		0.071	0.185	
800706	12.10	0.033	0.000	0.000	0.184				0.213		0.035	0.091	
800706	12.11	0.033	0.000	0.000	0.109				0.213		0.035	0.122	
800706	12.12	0.000	0.000	0.000	0.071				0.266		0.035	0.091	
800706	12.13	0.000	0.000	0.037	0.035				0.471		0.000	0.060	
800706	12.14	0.033	0.000	0.000	0.035				0.016		0.000	0.060	
800706	12.15	0.000	0.000	0.000	0.035				0.103		0.000	0.091	
800706	12.16	0.000	0.000	0.000	0.035				0.067		0.035	0.091	
800706	12.17	0.000	0.000	0.000	0.035				0.031		0.000	0.060	
800706	12.18	0.000	0.000	0.000	0.000				0.031		0.000	0.060	
800706	12.19	0.000	0.000	0.000	0.035				0.031		0.000	0.060	
800706	12.20	0.000	0.000	0.000	0.071				0.000		0.000	0.060	
800706	12.21	0.000	0.000	0.000	0.000				0.031		0.000	0.029	
800706	12.22	0.000	0.000	0.037	0.035				0.000		0.035	0.029	
800706	12.23	0.000	0.000	0.000	0.000				0.000		0.000	0.029	
800706	12.24	0.000	0.000	0.000	0.000				0.000		0.000	0.000	
800706	12.25	0.000	0.000	0.000	0.000				0.000		0.000	0.029	
800706	12.27	0.000	0.000	0.000	0.000				0.000		0.000	0.000	

RAINFALL INTENSITY mm/min.

RAINFALL EVENT No 9.

RAINGAUGE No :

DATE	TIME	1	2	3	4	5	6	7	8	9	10	11	12
790625	01.01	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.081	0.000	0.029
790625	01.02	0.000	0.000	0.000	0.000	0.000	0.036	0.000	0.032	0.000	0.122	0.000	0.060
790625	01.03	0.190	0.000	0.000	0.000	0.184	0.222	0.000	0.032	0.000	0.289	0.000	0.091
790625	01.04	0.308	0.000	0.000	0.000	0.453	0.260	0.000	0.176	0.502	0.542	0.218	0.248
790625	01.05	0.308	0.105	0.000	0.235	0.609	0.565	0.000	0.326	0.537	0.968	0.218	0.897
790625	01.06	0.268	0.564	0.000	0.521	0.609	0.604	0.000	0.954	0.363	0.584	0.181	0.897
790625	01.07	0.754	0.255	0.037	0.480	0.337	0.913	0.247	1.236	0.608	0.289	0.035	0.668
790625	01.08	0.754	0.142	0.352	0.439	0.260	0.450	0.137	0.914	1.002	0.081	0.035	0.635
790625	01.09	0.591	0.033	0.312	0.155	0.184	0.109	0.066	0.834	0.894	0.081	0.071	0.185
790625	01.10	0.190	0.033	0.114	0.115	0.184	0.036	0.000	0.326	0.679	0.040	0.035	0.091
790625	01.11	0.000	0.069	0.037	0.076	0.071	0.036	0.000	0.176	0.093	0.000	0.000	0.091
790625	01.12	0.000	0.033	0.000	0.115	0.071	0.036	0.000	0.103	0.029	0.040	0.035	0.029
790625	01.13	0.000	0.033	0.037	0.037	0.000	0.000	0.032	0.067	0.029	0.000	0.000	0.029
790625	01.14	0.000	0.000	0.000	0.037	0.035	0.036	0.000	0.000	0.029	0.000	0.000	0.000
790625	01.15	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.032	0.000	0.000	0.000	0.029
790625	01.16	0.000	0.033	0.000	0.037	0.000	0.000	0.000	0.000	0.029	0.000	0.000	0.000
790625	01.17	0.000	0.000	0.000	0.000	0.000	0.000	0.032	0.000	0.000	0.000	0.035	0.000
790625	01.18	0.000	0.000	0.000	0.000	0.000	0.036	0.000	0.000	0.000	0.040	0.000	0.000
790625	01.19	0.000	0.000	0.037	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
790625	01.20	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.032	0.000	0.000	0.000	0.000
790625	01.21	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.029	0.000	0.000	0.000
790625	01.22	0.000	0.000	0.000	0.000	0.035	0.000	0.000	0.000	0.000	0.000	0.000	0.000
790625	01.30	0.000	0.000	0.000	0.037	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
790625	01.36	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.029
790625	01.38	0.000	0.033	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
790625	01.46	0.036	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
790625	01.54	0.000	0.000	0.000	0.000	0.000	0.036	0.000	0.000	0.000	0.000	0.000	0.000
790625	01.59	0.000	0.000	0.000	0.000	0.000	0.000	0.032	0.000	0.000	0.000	0.000	0.000
790625	02.16	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.032	0.000	0.000	0.000	0.000

2:11

RAINFALL INTENSITY mm/min.

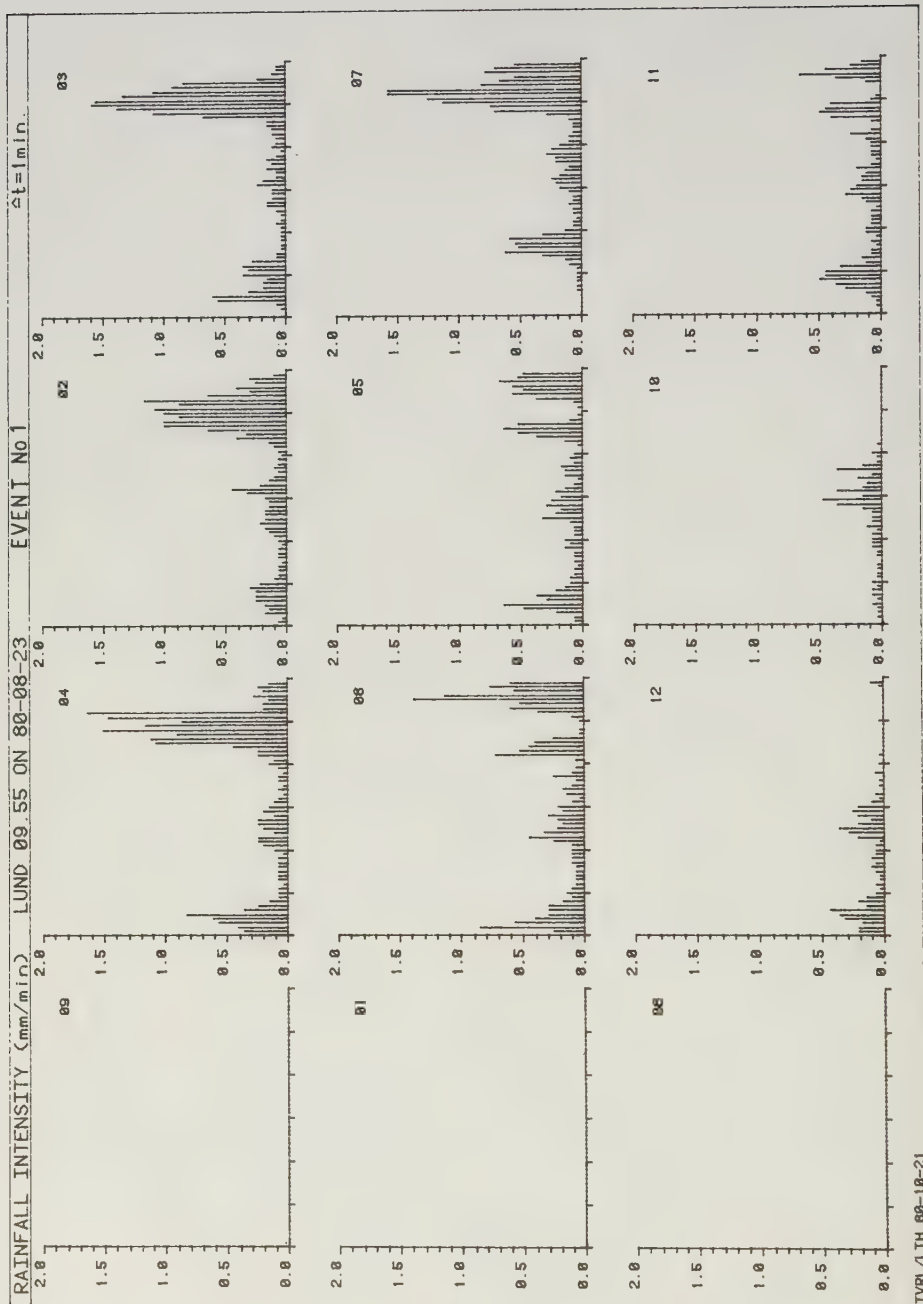
RAINFALL EVENT No 10.

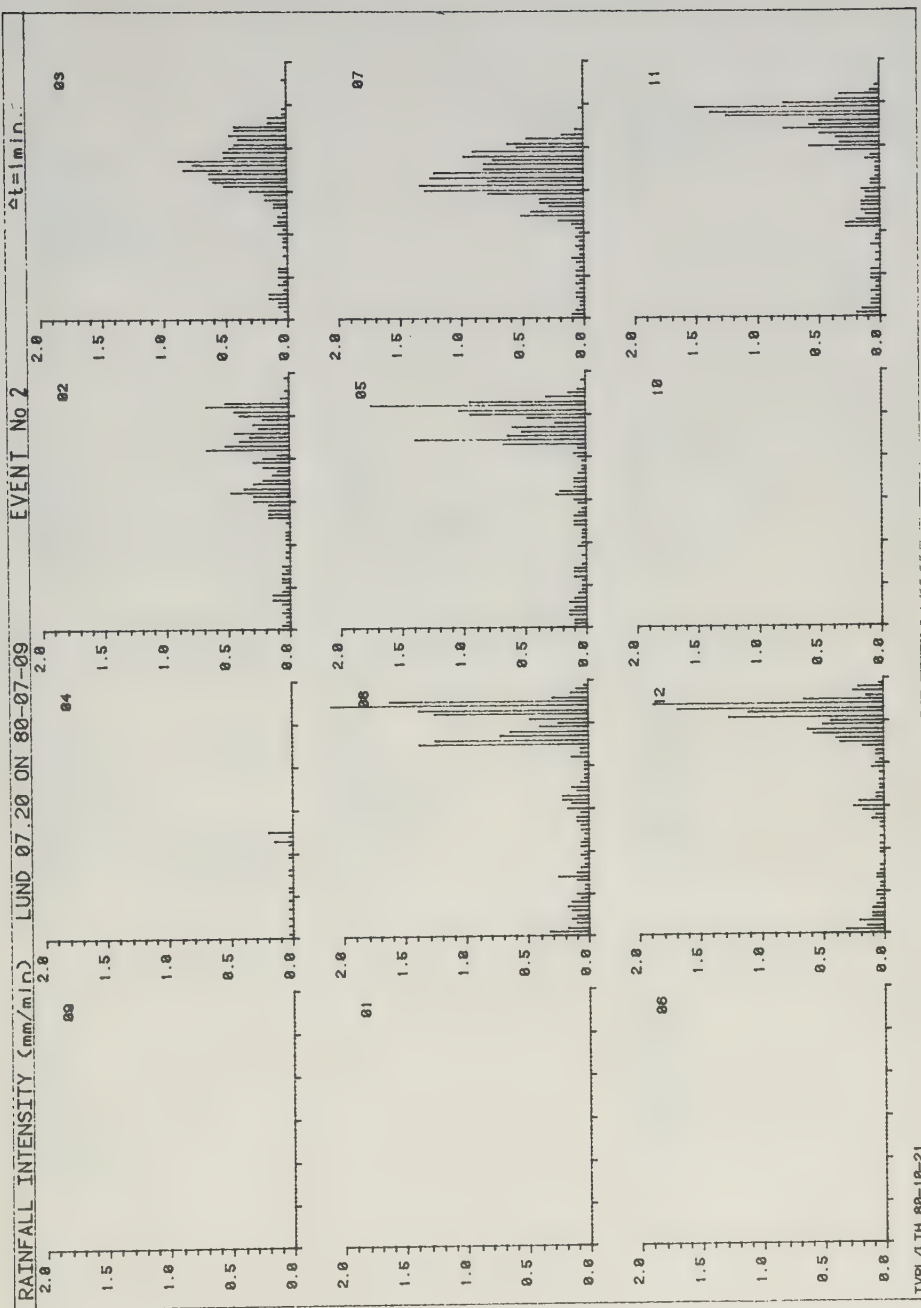
RAINGAUGE No :

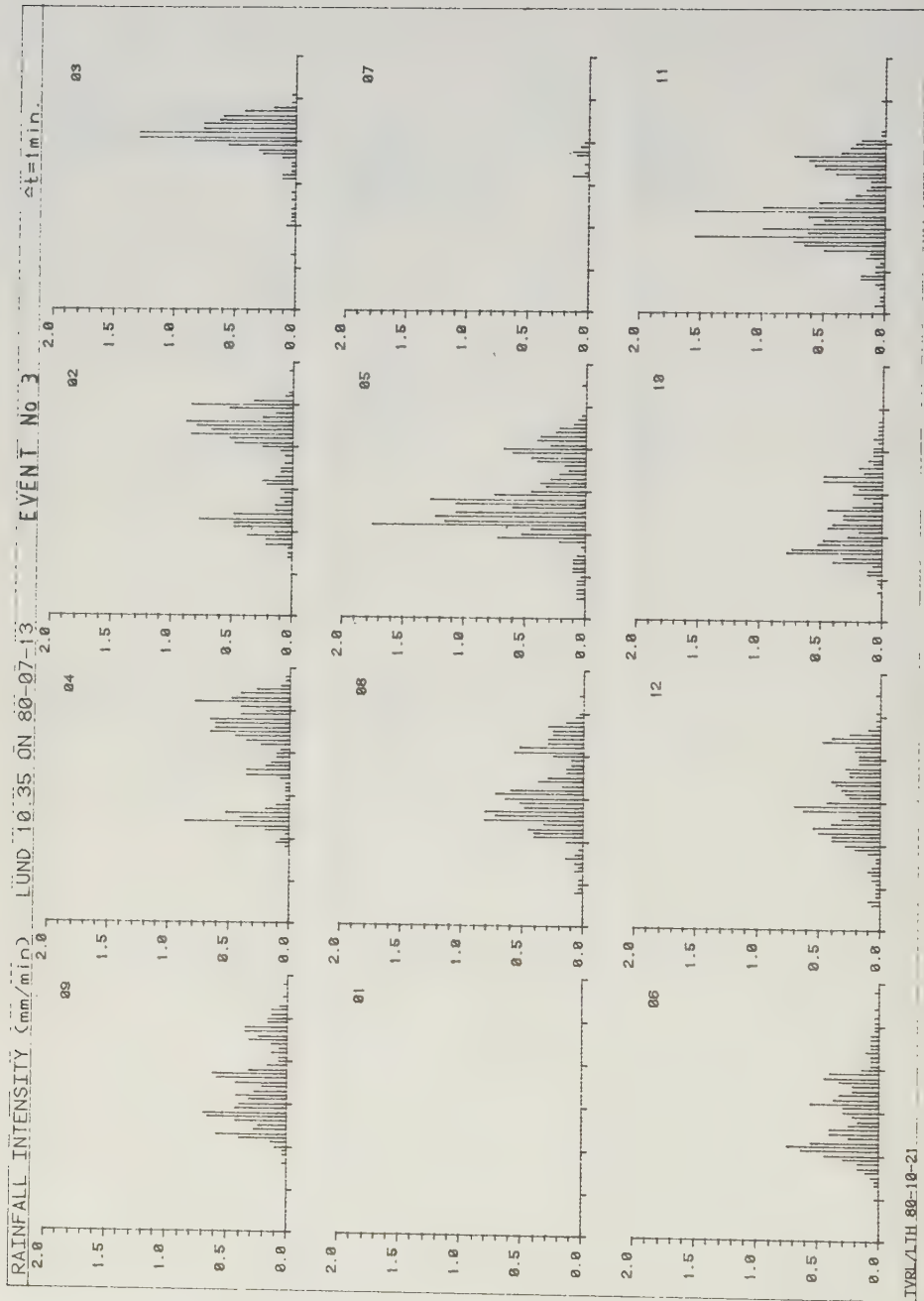
DATE	TIME	1	2	3	4	5	6	7	8	9	10	11	12
800709	05.00	0.000	0.000	0.000	0.000			0.137	0.000			0.000	0.000
800709	05.01	0.000	0.000	0.000	0.000			0.210	0.000			0.000	0.000
800709	05.02	0.033	0.037	0.000	0.000			0.359	0.000			0.000	0.000
800709	05.03	0.000	0.191	0.000	0.000			0.705	0.000			0.000	0.000
800709	05.04	0.000	0.312	0.037	0.000			0.550	0.000			0.000	0.000
800709	05.05	0.105	0.272	0.000	0.000			0.512	0.000			0.000	0.000
800709	05.06	0.255	0.511	0.000	0.000			0.359	0.000			0.000	0.000
800709	05.07	0.105	0.393	0.000	0.000			0.174	0.000			0.000	0.000
800709	05.08	0.105	0.393	0.000	0.000			0.705	0.000			0.000	0.000
800709	05.09	0.069	0.191	0.000	0.000			1.098	0.000			0.000	0.000
800709	05.10	0.179	0.350	0.037	0.000			0.284	0.000			0.035	0.000
800709	05.11	0.179	0.637	0.000	0.000			0.137	0.032			0.000	0.000
800709	05.12	0.069	1.259	0.000	0.000			0.032	0.000			0.000	0.000
800709	05.13	0.105	0.555	0.000	0.035			0.066	0.000			0.035	0.029
800709	05.14	0.447	0.272	0.037	0.000			0.032	0.032			0.035	0.000
800709	05.15	0.179	0.075	0.000	0.146			0.032	0.000			0.000	0.000
800709	05.16	0.105	0.075	0.000	0.146			0.032	0.000			0.035	0.000
800709	05.17	0.105	0.037	0.000	0.035			0.032	0.441			0.000	0.000
800709	05.18	0.033	0.037	0.000	0.000			0.102	0.067			0.000	0.000
800709	05.19	0.000	0.037	0.000	0.035			0.066	0.032			0.035	0.000
800709	05.20	0.069	0.037	0.000	0.035			0.359	0.000			0.000	0.000
800709	05.21	0.033	0.312	0.037	0.000			0.473	0.067			0.000	0.000
800709	05.22	0.033	0.272	0.000	0.000			0.210	0.032			0.000	0.029
800709	05.23	0.033	0.352	0.000	0.035			0.210	0.032			0.035	0.000
800709	05.24	0.255	0.555	0.037	0.000			0.032	0.000			0.035	0.000
800709	05.25	0.370	0.474	0.000	0.000			0.000	0.000			0.000	0.000
800709	05.26	0.105	0.596	0.000	0.035			0.000	0.032			0.000	0.000
800709	05.27	0.069	0.232	0.000	0.000			0.000	0.032			0.000	0.000
800709	05.28	0.033	0.000	0.000	0.000			0.000	0.032			0.000	0.000
800709	05.29	0.000	0.037	0.000	0.000			0.000	0.000			0.000	0.091
800709	05.30	0.000	0.000	0.037	0.035			0.102	0.000			0.035	0.185
800709	05.31	0.033	0.000	0.000	0.035			0.359	0.288			0.000	0.153
800709	05.32	0.000	0.000	0.000	0.000			0.066	0.176			0.000	0.060
800709	05.33	0.000	0.153	0.000	0.000			0.066	0.067			0.000	0.000
800709	05.34	0.033	0.474	0.037	0.035			0.102	0.067			0.000	0.000
800709	05.35	0.293	0.352	0.000	0.000			0.137	0.032			0.035	0.029
800709	05.36	0.408	0.114	0.000	0.000			0.705	0.000			0.000	0.000
800709	05.37	0.525	0.192	0.000	0.035			0.744	0.000			0.000	0.000
800709	05.38	0.331	0.232	0.000	0.000			0.322	0.067			0.000	0.000
800709	05.39	0.217	0.596	0.000	0.000			0.247	0.032			0.107	0.000
800709	05.40	0.255	0.312	0.037	0.035			0.247	0.032			0.107	0.029
800709	05.41	0.486	0.352	0.000	0.109			0.102	0.000			0.035	0.000
800709	05.42	0.255	0.272	0.000	0.767			0.102	0.067			0.107	0.312
800709	05.43	0.105	0.153	0.000	0.375			0.137	0.460			0.218	0.122
800709	05.44	0.179	0.075	0.037	0.109			0.102	0.636			0.292	0.091
800709	05.45	0.142	0.114	0.000	0.296			0.322	0.250			0.366	0.091
800709	05.46	0.105	0.037	0.000	0.184			0.174	0.213			0.218	0.029
800709	05.47	0.033	0.114	0.000	0.222			0.066	0.250			0.035	0.060
800709	05.48	0.179	0.075	0.000	0.492			0.032	0.441			0.035	0.060
800709	05.49	0.033	0.075	0.000	0.184			0.000	0.518			0.000	0.029
800709	05.50	0.105	0.153	0.000	0.035			0.000	0.441			0.000	0.000
800709	05.51	0.033	0.037	0.037	0.035			0.000	0.032			0.000	0.029
800709	05.52	0.033	0.037	0.000	0.000			0.032	0.067			0.035	0.000
800709	05.53	0.000	0.000	0.000	0.035			0.032	0.000			0.000	0.029
800709	05.54	0.033	0.000	0.000	0.000			0.032	0.032			0.000	0.060
800709	05.55	0.000	0.037	0.037	0.000			0.032	0.067			0.035	0.060
800709	05.56	0.000	0.000	0.000	0.035			0.032	0.067			0.000	0.029
800709	05.57	0.000	0.037	0.000	0.000			0.032	0.032			0.000	0.029

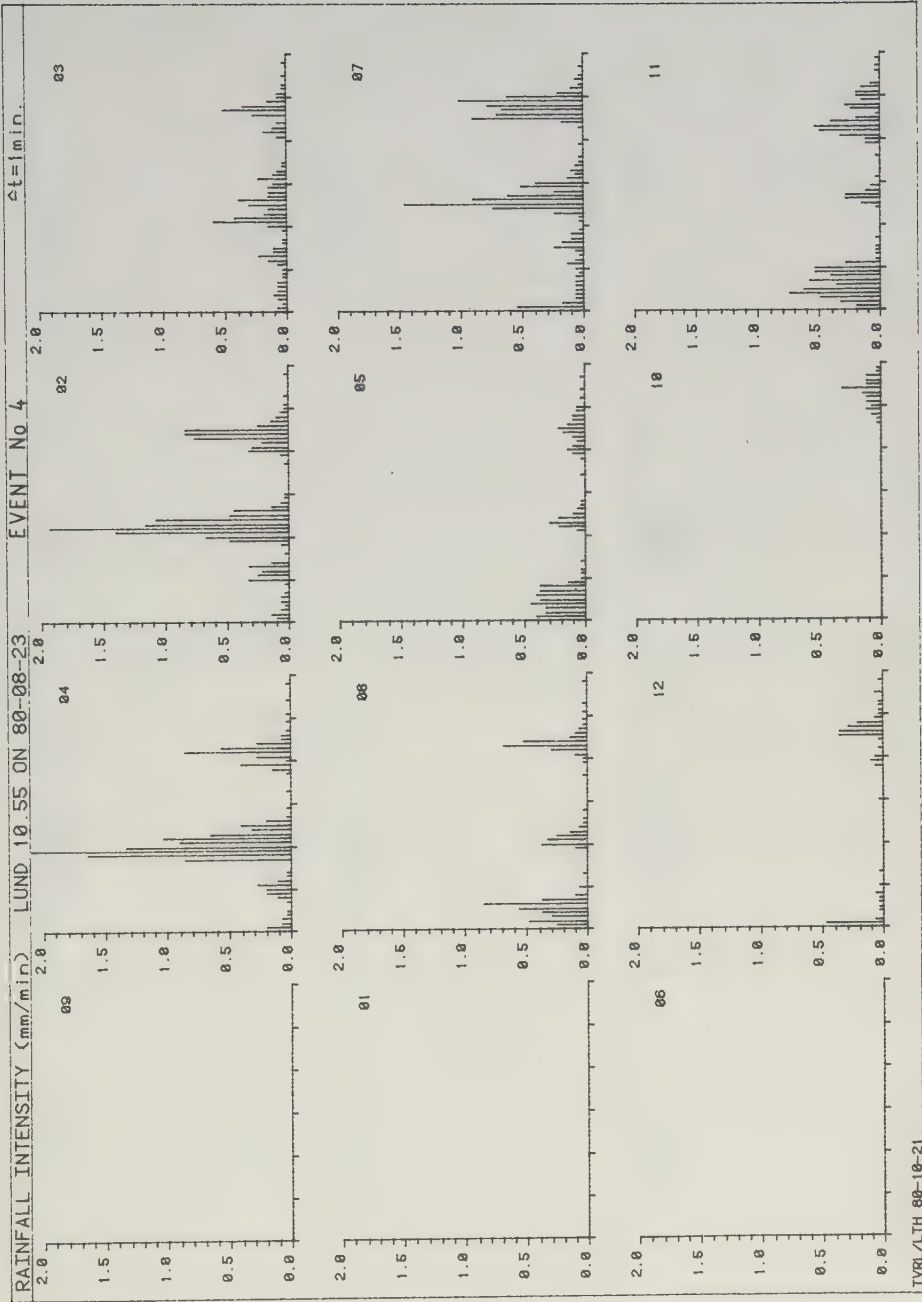
APPENDIX 3

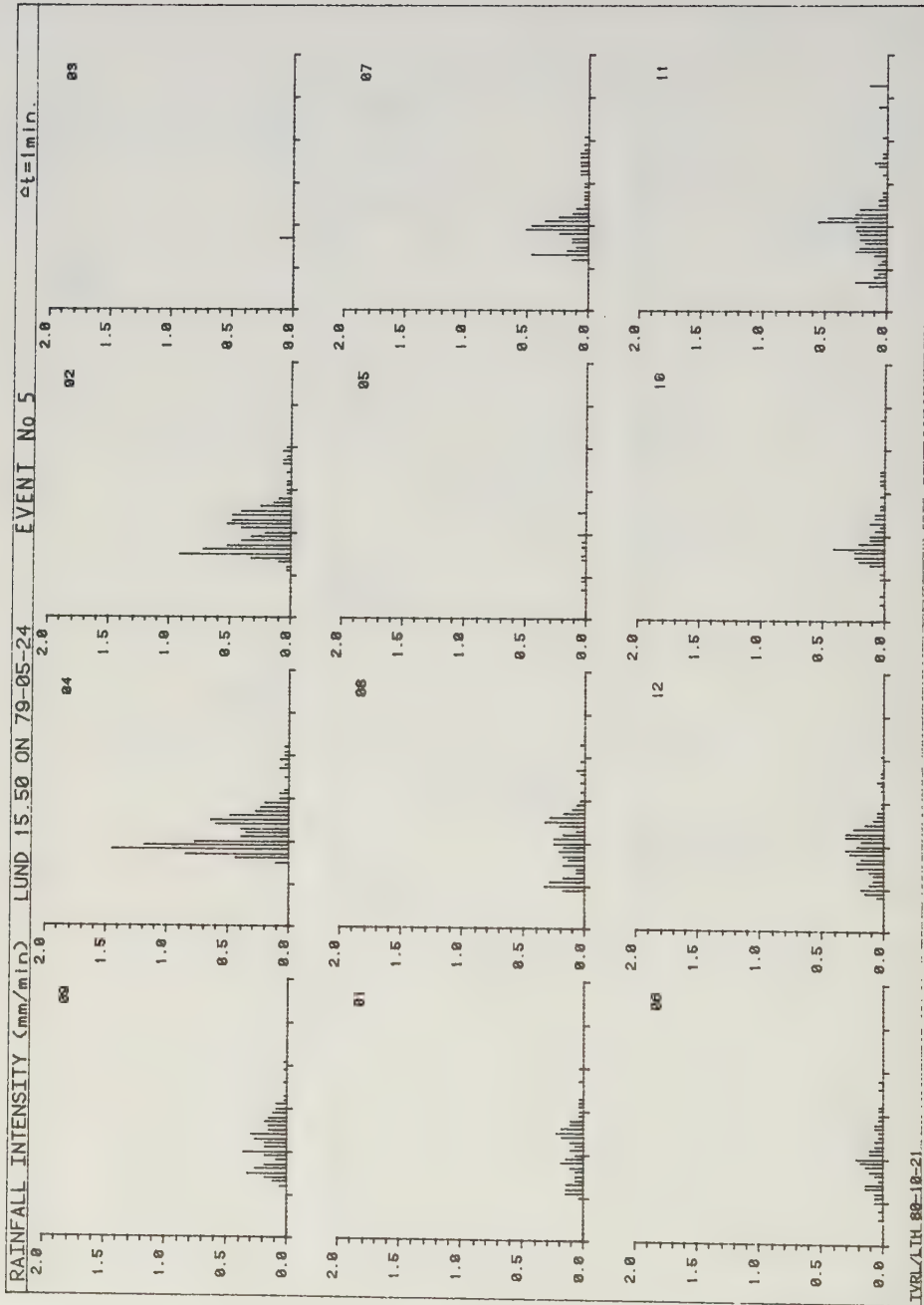
Computer Generated Hyetograph-Diagrams
for 10 Extreme Rainfall Events in Lund



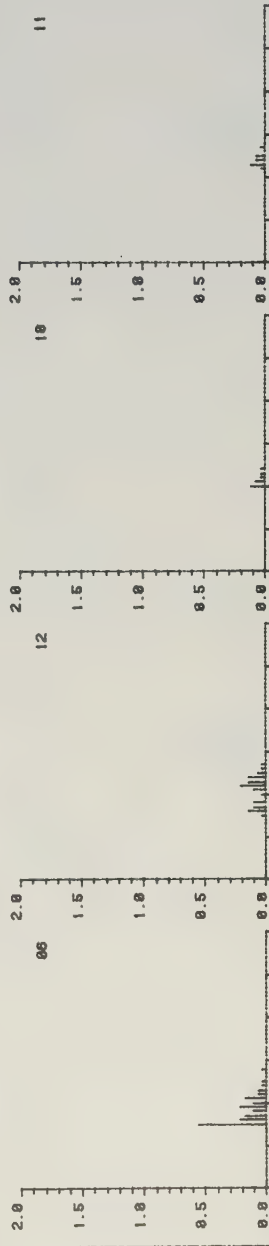
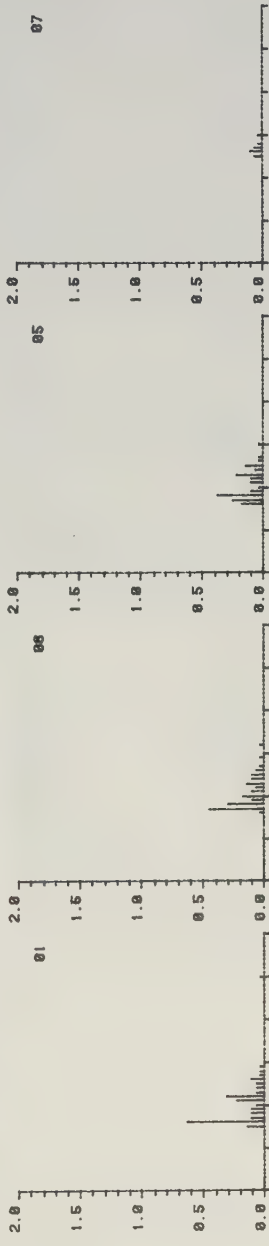
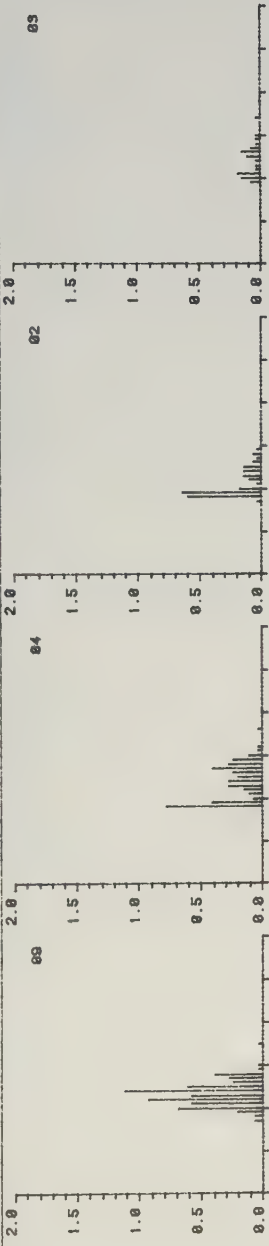








RAINFALL INTENSITY (mm/min) LUND 14.10 ON 79-09-21 EVENT No 6 $\Delta t = 1 \text{ min.}$

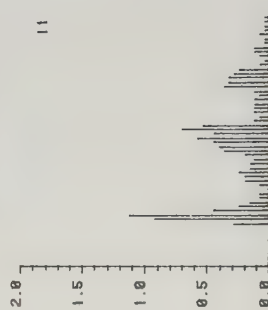
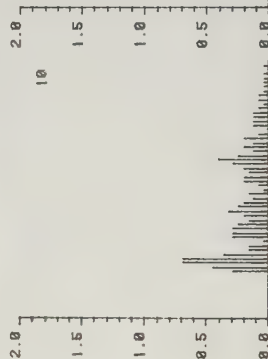
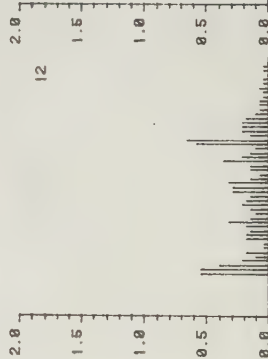
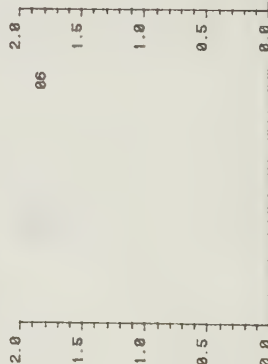
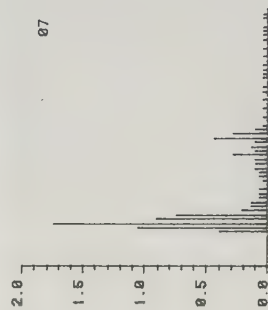
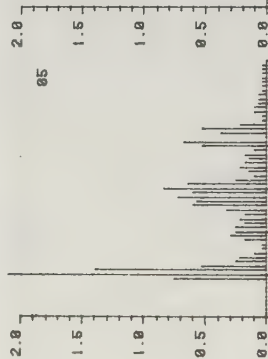
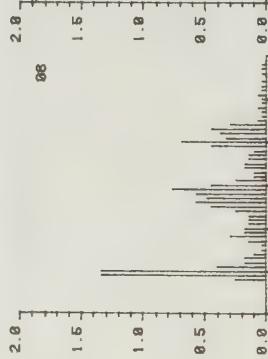
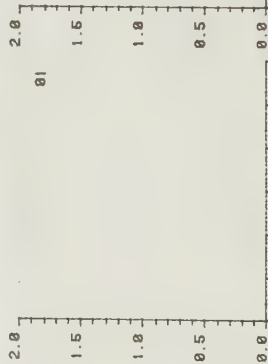
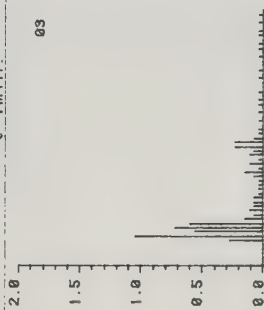
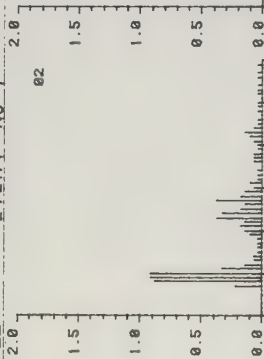
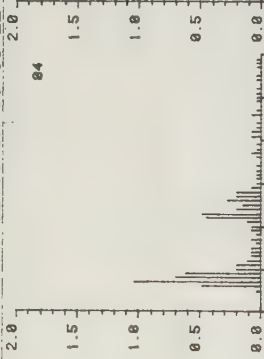
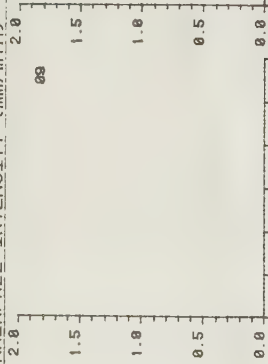


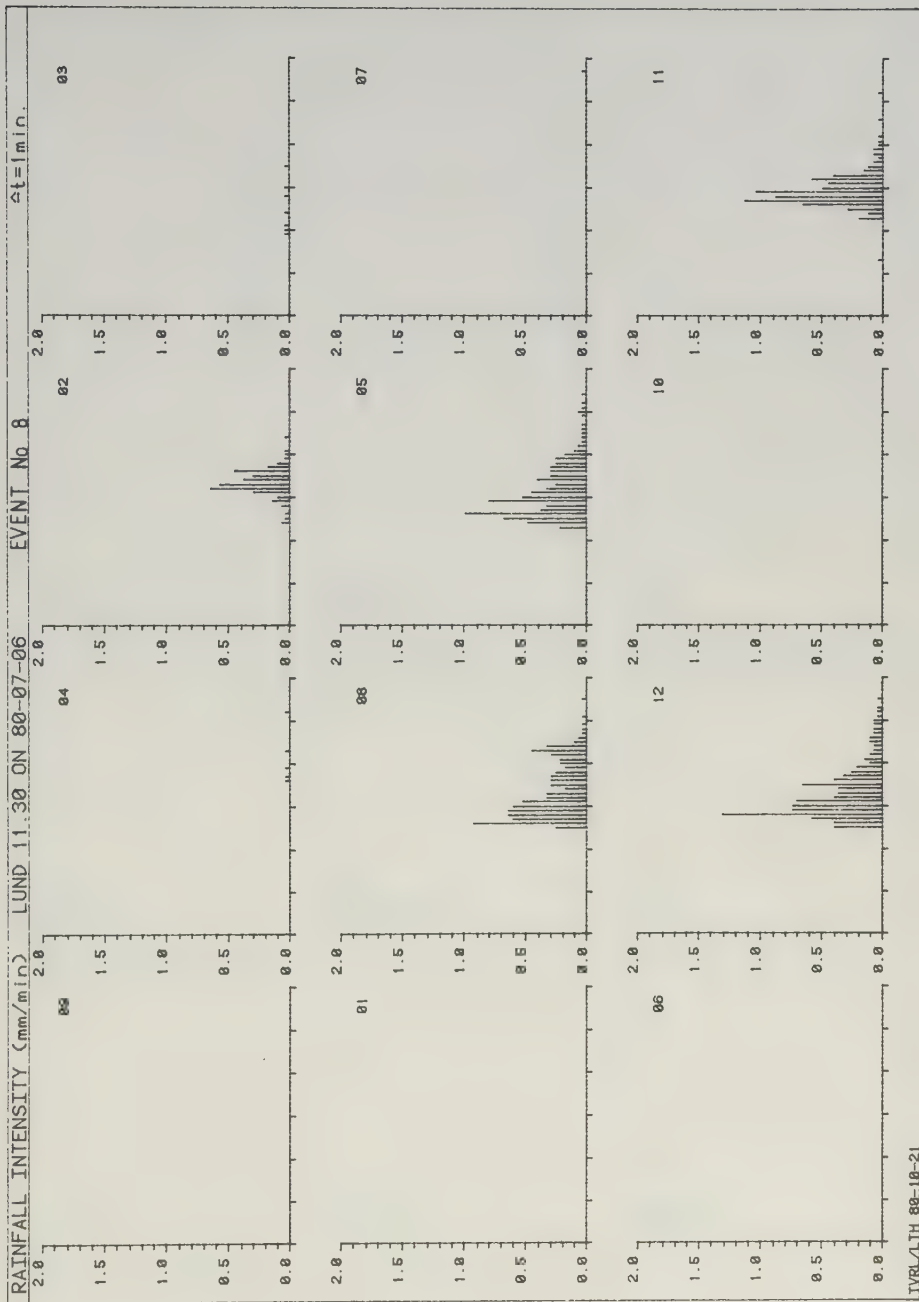
TVBL/1TH 88-10-21

RAINFALL INTENSITY (mm/min)

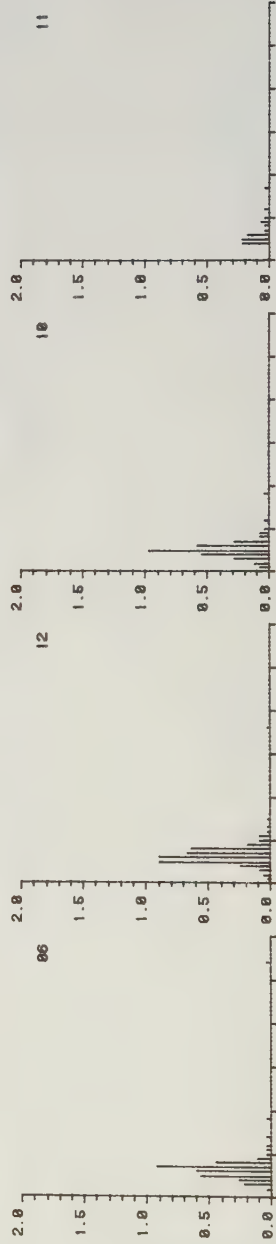
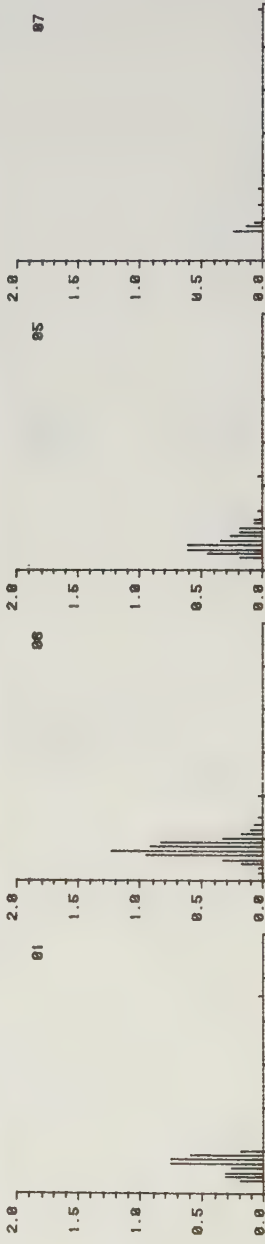
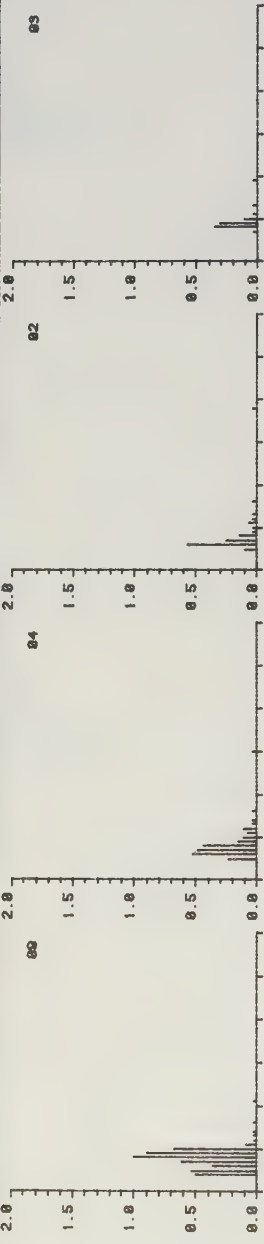
LUND 22 00 ON 80-08-22

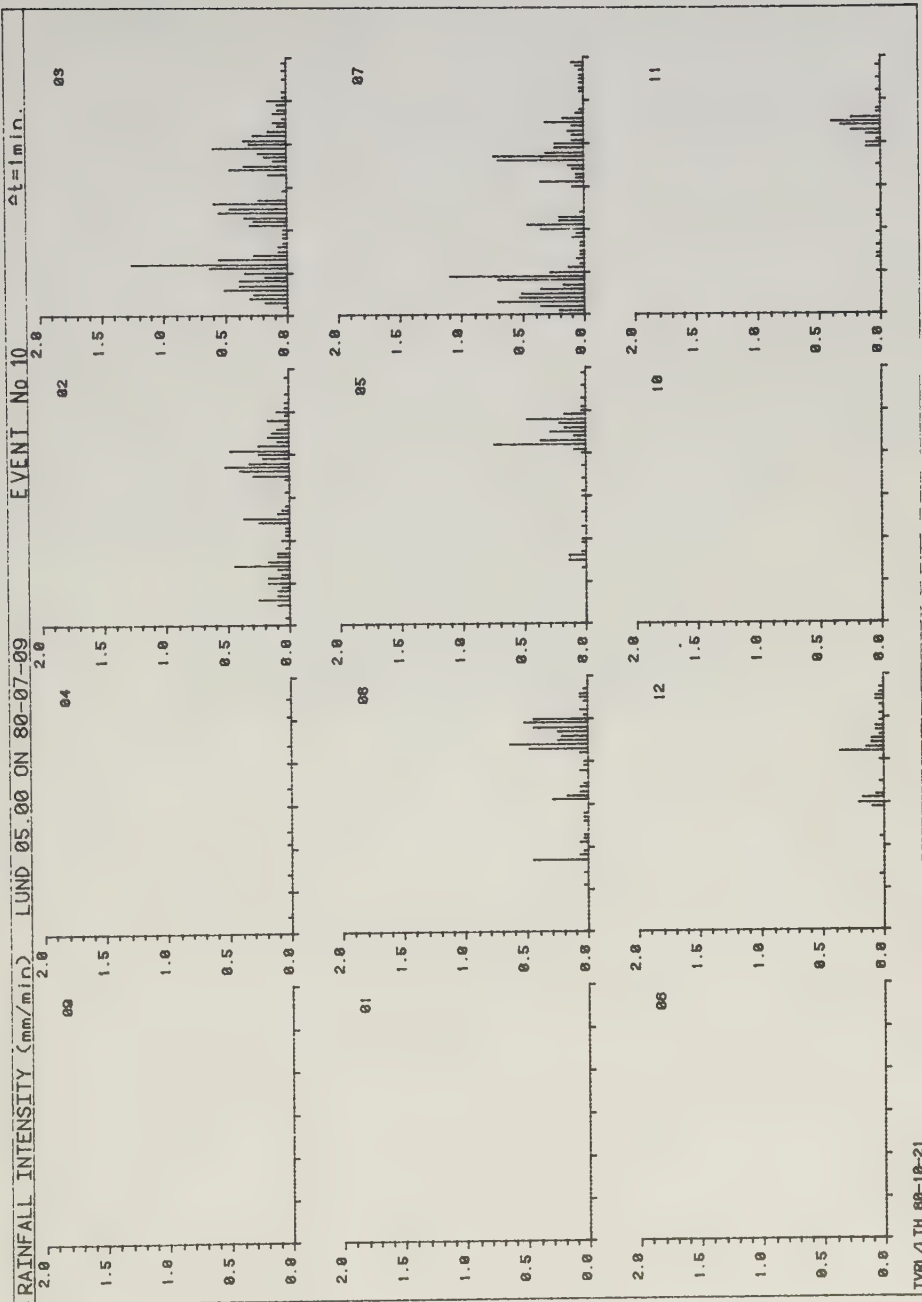
EVENT No 7

 $\Delta t = 1 \text{ min}$ 



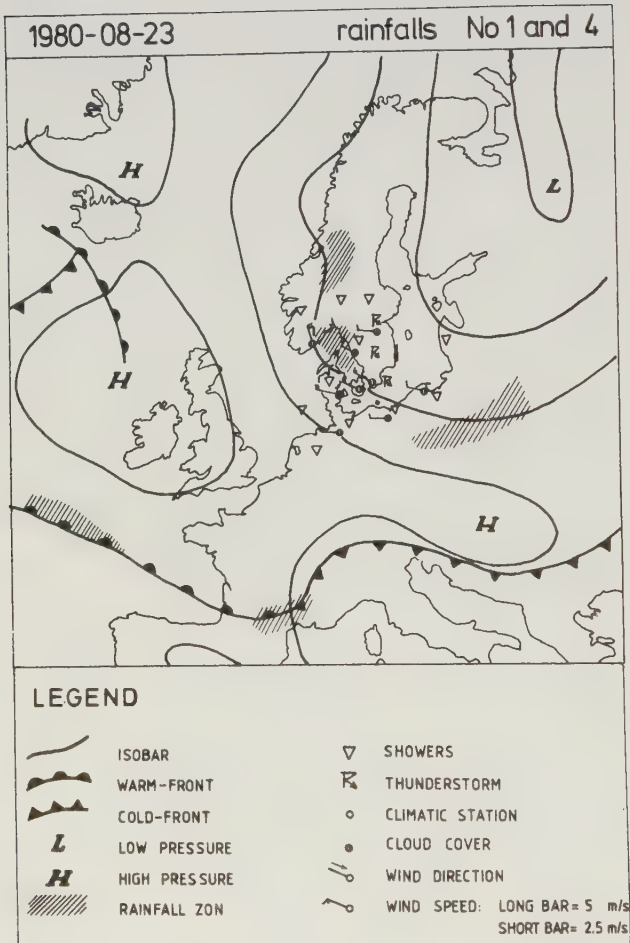
RAINFALL INTENSITY (mm/min) LUND 01.00 ON 79-06-25 EVENT No 9 $\Delta t = 1 \text{ min}$



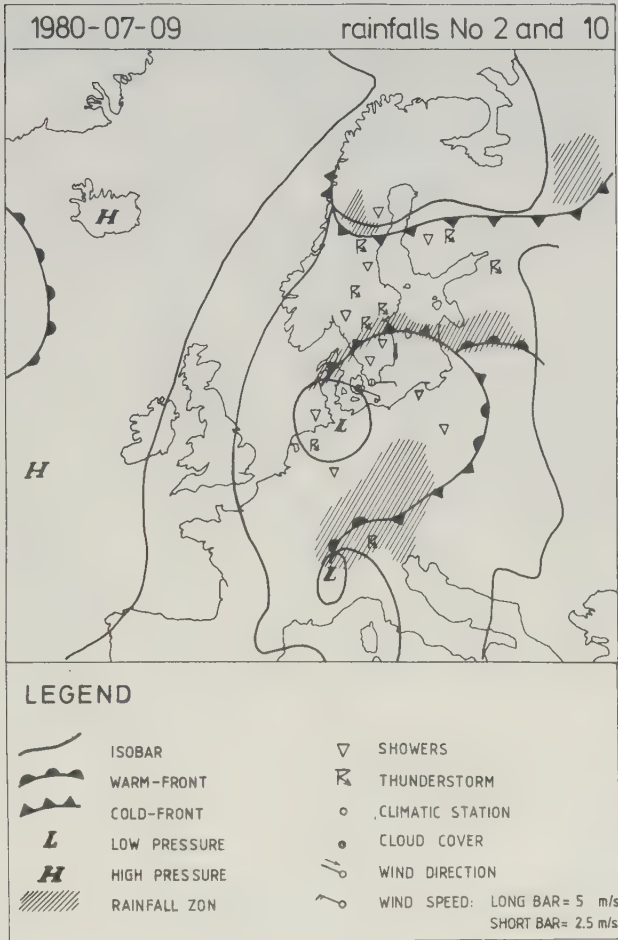


APPENDIX 4

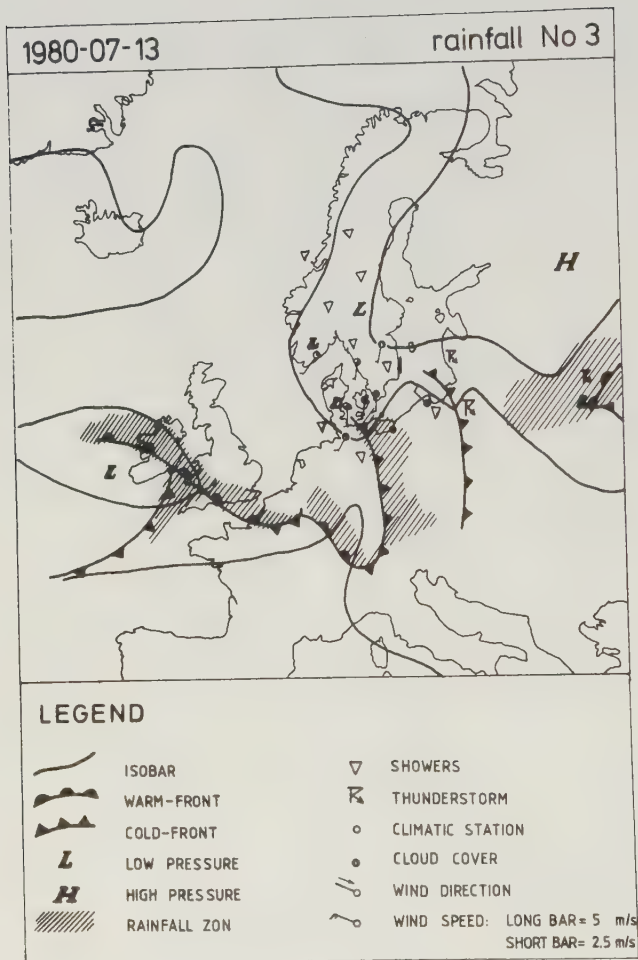
Synoptic Maps Giving Weather Situation
in Northern Europe During the Days with
Extreme Rainfall Events Observed in Lund



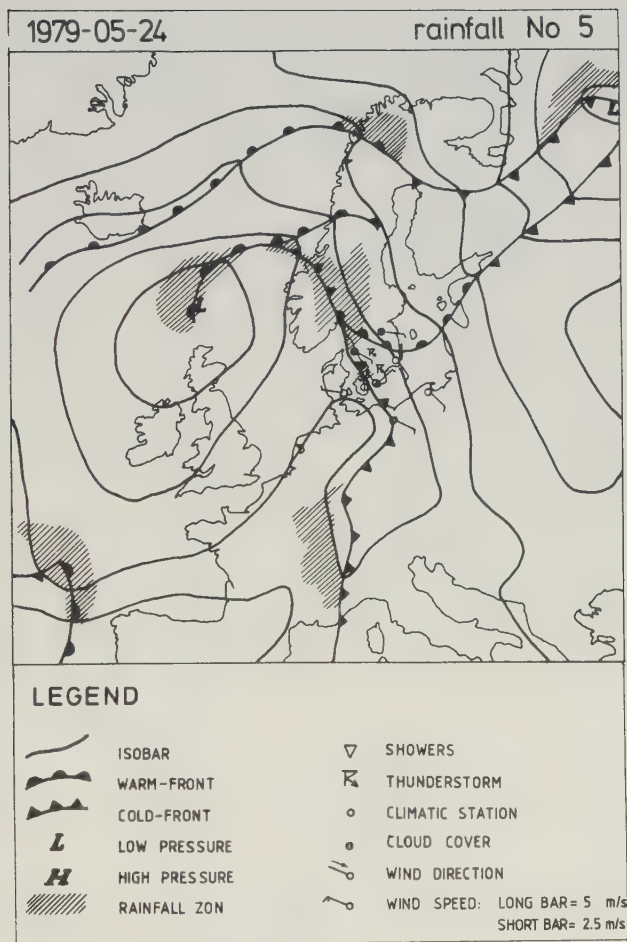
Low pressure zone over North Europe is almost still.
 Numerous showers occur in South-West of Sweden.
 Strong wind from West.



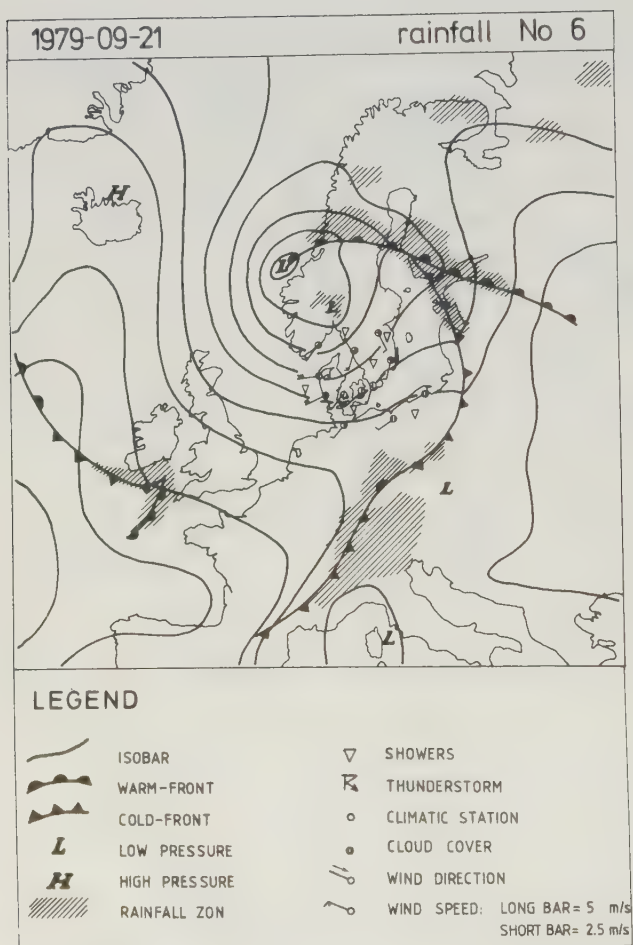
Low pressure zone over Holland moves slowly to North-East and is foregone by showers and thunderstorms. Increasing wind from South-East.



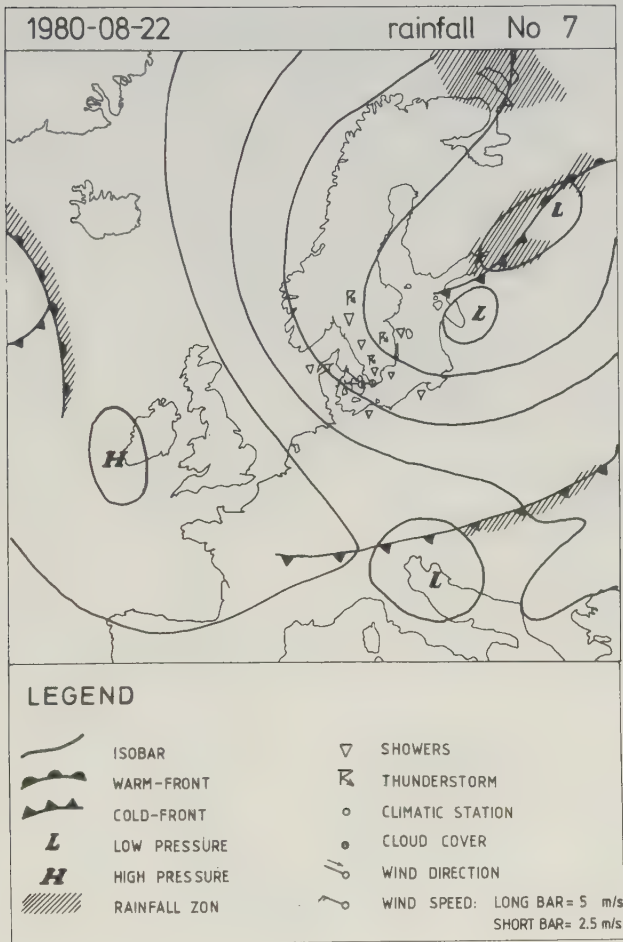
Low pressure zone over Baltic sea moves to North-East.
 A weak cold front passes the Southern part of Sweden
 and moves to the East. On the rear of the cold front
 Cumulonimbus clouds and local thunderstorms can occur.



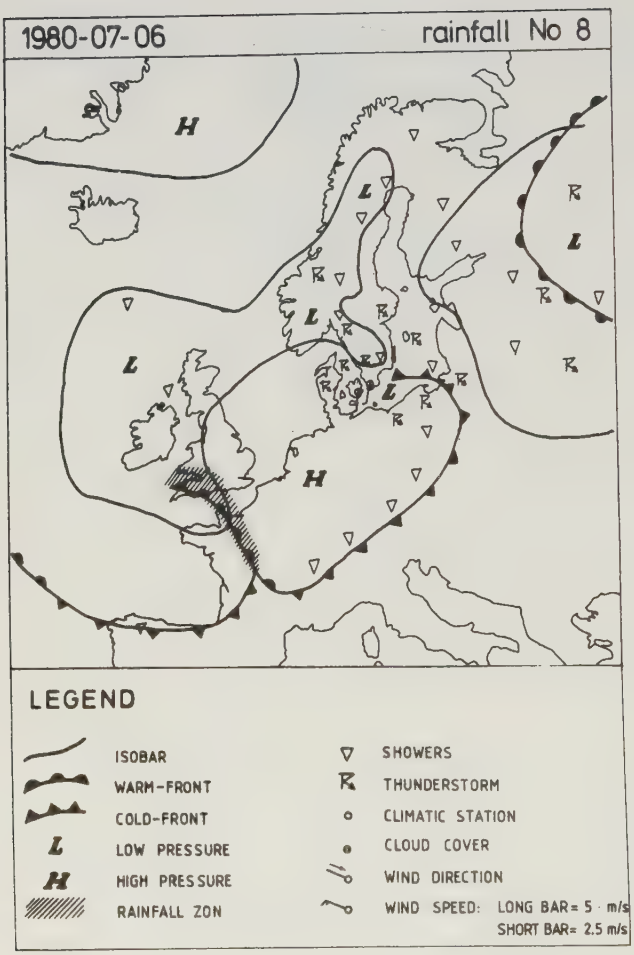
Low pressure zone moves North over Southern part of Sweden. On the rear of it a great deal of thunderstorms can occur. Cold air moves over Southern part of Sweden together with moist wind from South-East.



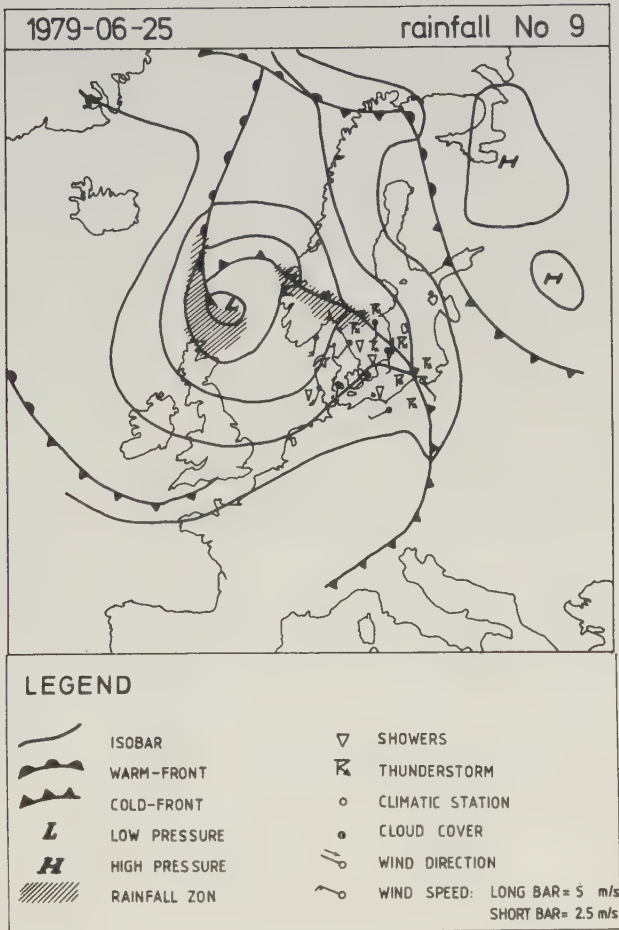
Low pressure zone moves over Southern part of Norway.
 Rainfall zone moves to South of Sweden in connection
 to increasing South-West wind.



Low pressure zon over Northern part of Scandinavia is almost still. Numerous showers or thunderstorms occur over South-West part of Sweden. Strong wind from West or North-West.



Small low pressure zon over Denmark moves to Southern part of Baltic sea. Numerous local showers or thunderstorms over Southern part of Sweden. Week wind from South.



Low pressure zone over North sea intensifies and moves North. Numerous showers or thunderstorms over Southern part of Sweden. Increasing wind from South-East.

APPENDIX 5

Triade-Program for Calculation of
Rainfall Velocity and Direction


```

5      TRIADE PROGRAM CALCULATES STORM VELOCITY AND DIRECTION
6
7
10     DIMENSION X(12),Y(12),T(12)
20     DIMENSION A(3,3),B(3),R(2),RS(2),V(2)
30     DATA X /1.812,3.996,5.196,3.516,3.024,1.164,5.820,2.568,
40     *1.704,1.776,3.780,2.340/
50     DATA Y /3.648,3.552,3.444,4.716,2.676,2.988,1.560,3.396,
60     *5.088,0.948,1.380,2.340/
70     OMV=100./6.
80     EPS=1E-10
90     PI=4.*ATAN(1.)
100    8 CONTINUE
110    READ(*,*,END=9) IDUM,JDUM,T
120    WRITE(6,16)
130    WRITE(6,17) IDUM,JDUM,T
140    RS(1)=0.0
150    RS(2)=0.0
160    VS=0.0
170    SV2=0.0
180    I=0
190    NI=0
200    1 CONTINUE
210    I=I+1
220    IF(T(I) .LT. 0.0) GO TO 1
230    IF(I .GT. 10) GO TO 4
240    J=I
250    2 CONTINUE
260    J=J+1
270    IF(T(J) .LT. 0.0) GO TO 2
280    IF(J .GT. 11) GO TO 1
290    K=J
300    3 CONTINUE
310    K=K+1
320    IF(T(K) .LT. 0.0) GO TO 3
330    IF(K .GT. 12) GO TO 2
340 C   WRITE(6,10) I,J,K
350 C   WRITE(6,11) X(I),Y(I),T(I)
360 C   WRITE(6,11) X(J),Y(J),T(J)
370 C   WRITE(6,11) X(K),Y(K),T(K)
380    A(1,3)=1.0
390    A(2,3)=1.0
400    A(3,3)=1.0
410    A(1,1)=X(I)
420    A(2,1)=X(J)
430    A(3,1)=X(K)
440    A(1,2)=Y(I)
450    A(2,2)=Y(J)
460    A(3,2)=Y(K)
470    B(1)=T(I)
480    B(2)=T(J)
490    B(3)=T(K)
500    CALL SOLVE(A,B)
->

```

```

510      R(1)=B(1)
520      R(2)=B(2)
530      VA=1./SQRT(R(1)*R(1)+R(2)*R(2))
540      R(1)=R(1)*VA
550      R(2)=R(2)*VA
560 C    WRITE(6,12) R
570 C    WRITE(6,13) VA
580      V(1)=R(1)*VA
590      V(2)=R(2)*VA
600 C    WRITE(6,12) V
610      RS(1)=RS(1)+R(1)
620      RS(2)=RS(2)+R(2)
630      VS=VS+VA
640      SV2=SV2+VA*VA
650      NI=NI+1
660      GO TO 3
670 4    CONTINUE
680      FNI=FLOAT(NI)
690      VM=VS/FNI
700      VARV=(SV2-VM*VM*FNI)/(FNI-1.0)
710      STV=SQRT(VARV)
720      RABS=RS(1)*RS(1)+RS(2)*RS(2)
730      RABS=SQRT(RABS)
740      SPRI=RABS/FNI
750      VMMS=VM*OMV
760      IF (ABS(RS(2)).LT.EPS) RS(2)=SIGN(EPS,RS(2))
770      FI=ATAN2(RS(1),RS(2))
780      IF (FI.LT. 0.0) FI=FI+2.*PI
790      GRAD=FI*180./PI
800      WRITE(6,15) RS,SPRI
810      WRITE(6,18) GRAD
820      WRITE(6,14) VM,STV,VMMS
822      WRITE(11,20) IDUM,JDUM,GRAD,VMMS
830      GO TO 8
840 10   FORMAT(1X,3I4)
850 11   FORMAT(1X,3F10.3)
860 12   FORMAT(1X,2F10.3)
870 13   FORMAT(1X,F10.3)
880 14   FORMAT(1X,'HASTIGHET MV.',1X,F6.3,' KM/MIN   ST.AVV.',1X,F6.3,
890      * ' KM/MIN   HASTIGHET MV',F8.3,' M/S')
900 15   FORMAT(' RIKT. X',1X,F8.3,' RIKT. Y',1X,F8.3,      SPRI.'1X,F6.
910 16   FORMAT(1H0,'DATUM TID INLÄSTA TIDPUNKTER')
920 17   FORMAT(1X,I6,1X,I4,12F5.1)
930 18   FORMAT(1X,'BÄRING I GRADER',F5.0)
940 19   FORMAT('ONORMALT SLUT PÅ "TRIAD"')
942 20   FORMAT(2I6,F6.0,F8.3)
950 9    CONTINUE
960      WRITE(6,19)
970      STOP
980      END
END OF FILE
->

```

```

1      SUBROUTINE SOLVE(A,B)
2      DIMENSION A(3,3) , B(3)
3      A(1,2)=A(1,2)/A(1,1)
4      A(1,3)=A(1,3)/A(1,1)
5      B(1)=B(1)/A(1,1)
6      A(2,2)=A(2,2)-A(2,1)*A(1,2)
7      A(3,2)=A(3,2)-A(3,1)*A(1,2)
8      A(2,3)=(A(2,3)-A(2,1)*A(1,3))/A(2,2)
9      B(2)=(B(2)-A(2,1)*B(1))/A(2,2)
10     A(3,3)=A(3,3)-A(3,1)*A(1,3)-A(3,2)*A(2,3)
11     B(3)=(B(3)-A(3,1)*B(1)-A(3,2)*B(2))/A(3,3)
12     B(2)=B(2)-A(2,3)*B(3)
13     B(1)=B(1)-A(1,3)*B(3)-A(1,2)*B(2)
14     RETURN
15     END
END OF FILE
->

```

APPENDIX 6

List of Rainfall Movement Parameters
for 400 Rainfall Events in Lund

TABLE EXPLANATIONS:

Column No	Explanation
1	Event No
2	Date
3	Time, hour, minute
4	Storm movement direction, degrees clockwise from North.
5	Storm movement velocity, m/s
6	Maximum 5 min. rainfall intensity, mm/min
7	Maximum 1 min. rainfall intensity, mm/min
8	Wind direction, degrees clockwise from North, 800 mb level
9	Wind velocity, m/s, 800 mb level
10	Wind direction, degrees clockwise from North, 700 mb level
11	Wind velocity, m/s, 700 mb level
12	Wind direction, degrees clockwise from North, 600 mb level
13	Wind velocity, m/s, 600 mb level
14	Wind direction, degrees clockwise from North, ground level
15	Wind velocity, m/s, ground level

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	790309	712	67.	8.767	.12	.10								
2	790312	1143	75.	4.619	.14	.10								
3	790322	1408	351.	4.360	.14	.10								
4	790326	142	337.	4.006	.20	.13								
5	790326	1856	7.	10.208	.30	.17								
6	790326	1919	13.	11.788	.22	.14								
7	790326	2020	294.	8.756	.49	.25								
8	790326	2027	294.	6.846	.49	.30								
9	790326	2036	11.	13.775	.94	.53								
10	790326	2104	89.	19.398	.94	.53								
11	790326	2201	303.	12.179	.23	.14								
12	790424	1251	41.	13.387	.11	.09								
13	790430	1748	148.	21.200	.15	.08								
14	790518	1658	54.	4.291	.55	.36	30	13	40	15	35	19	338	2
15	790522	630	338.	8.797	.28	.23	50	7	45	7	27	11	0	6
16	790524	303	334.	11.741	.31	.17	25	11	10	19	15	19	333	6
17	790524	524	312.	14.460	.31	.17	25	11	10	19	15	19	248	1
18	790524	1521	352.	9.062	.29	.22	350	12	0	19	0	17	135	4
19	790524	1601	24.	5.726	1.45	.94	350	12	0	15	0	17	135	4
20	790524	1614	354.	16.201	.66	.50	350	12	0	15	0	17	135	4
21	790524	2120	348.	20.473	.55	.22	45	12	15	18	40	24	248	4
22	790524	1605	333.	9.986	1.45	.94	350	12	0	15	0	17	135	4
23	790524	2118	311.	21.860	.55	.22	15	18	40	24	20	27	248	4
24	790525	2021	1.	20.353	.14	.09	20	11	18	9	8	11	0	1
25	790625	104	10.	17.273	1.25	.87	355	15	345	19	350	22	68	4
26	790625	105	352.	19.866	1.25	.87	355	15	345	19	350	22	68	4
27	790625	235	352.	26.743	.19	.13	355	15	345	19	350	22	68	4
28	790630	1441	110.	7.951	.50	.35	95	12	100	14	100	14	90	11
29	790630	2147	58.	10.604	.37	.23	125	13	95	10	95	16	90	11
30	790701	520	10.	8.993	.22	.10	105	12	98	13	95	13	90	7
31	790701	858	102.	10.719	.56	.16	105	12	98	13	95	13	90	7
32	790701	931	127.	11.091	.50	.20	105	9	115	9	125	7	90	7
33	790701	1914	159.	7.217	.41	.15	125	11	115	12	130	10	113	8
34	790701	1927	129.	15.904	.24	.12	125	11	115	12	130	10	113	8
35	790709	622	103.	6.517	.12	.09	130	17	140	13	150	8	90	7
36	790709	626	91.	4.682	.12	.09	130	17	140	13	150	8	90	7
37	790717	1036	166.	8.734	.31	.23	165	8	180	9	185	13	113	5
38	790717	1039	179.	10.066	.39	.23	165	8	180	9	185	13	113	5
39	790719	1722	134.	13.595	.26	.11	95	20	115	19	108	24	90	10
40	790724	1303	122.	10.096	.24	.10	80	11	90	12	85	16	90	7
41	790724	1447	74.	6.612	.17	.14	80	11	90	12	85	16	90	7
42	790730	239	16.	12.574	.83	.50	13	7	0	8	55	11	338	3
43	790802	113	96.	29.102	.28	.17	15	15	15	18	40	21	338	4
44	790802	1558	70.	34.197	.28	.18	65	19	65	22	55	28	45	7
45	790810	1217	326.	9.075	.29	.23	230	14	270	11	305	11	203	8
46	790810	1230	268.	7.841	.29	.23	230	14	270	11	305	11	203	8
47	790811	429	164.	7.745	1.35	.60	115	7	180	4	210	4	135	7
48	790823	2219	0.	10.240	.66	.32	25	10	30	14	15	19	338	5
49	790825	902	318.	8.160	.66	.54	270	5	290	4	305	4	225	2
50	790825	908	307.	4.522	.66	.54	270	5	290	4	305	4	225	2

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51	790826	335	144.	7.208	.28	.12	175	15	150	11	180	9	158	3
52	790826	1806	183.	7.942	.47	.22	145	12	155	8	160	7	135	8
53	790826	1750	224.	2.805	.28	.16	145	12	155	8	160	7	135	8
54	790827	444	99.	7.160	.32	.21	148	23	160	21	175	11	113	11
55	790827	610	120.	5.119	.65	.52	148	23	160	21	175	11	113	11
56	790827	1107	66.	9.422	.22	.12	140	18	140	16	145	18	90	11
57	790827	1229	83.	10.984	.23	.11	140	18	140	16	145	18	90	11
58	790827	2220	130.	12.034	.25	.15	155	15	148	14	150	13	113	7
59	790914	1528	101.	13.488	1.29	.72	75	13	80	20	75	25	68	11
60	790914	1923	100.	11.584	.64	.36	70	17	65	17	75	18	0	3
61	790915	545	157.	9.711	.32	.17	135	13	145	15	140	15	158	7
62	790915	603	167.	8.294	.96	.56	135	13	145	15	140	15	158	7
63	790915	603	208.	4.416	.96	.56	135	13	145	15	140	15	158	7
64	790917	2230	140.	18.387	.14	.10	100	20	100	24	90	25	68	10
65	790918	1139	136.	17.086	.12	.09	85	29	88	28	90	29	45	10
66	790920	1654	111.	14.698	.14	.11	50	20	50	22	50	22	68	7
67	790920	1719	57.	22.659	.33	.23	50	20	50	22	50	22	68	7
68	790920	1728	70.	19.771	1.04	.46	50	20	50	22	50	22	68	7
69	790921	1426	143.	6.619	1.12	.76	90	17	85	16	65	22	68	12
70	790921	1426	153.	6.763	1.12	.76	90	17	85	16	65	22	68	12
71	790921	1432	33.	9.674	1.12	.76	90	17	85	16	65	22	68	12
72	790926	1032	88.	10.441	.15	.11	90	14	80	15	80	18	45	8
73	791021	1204	107.	16.687	.16	.12								
74	791021	1752	137.	7.854	.32	.22								
75	791102	255	72.	2.487	.22	.16								
76	791104	1246	128.	15.255	.12	.11								
77	791106	2256	209.	6.623	.28	.13								
78	791107	102	237.	6.843	.41	.15								
79	791109	1656	101.	7.273	.36	.29								
80	791204	515	101.	12.733	.37	.22								
81	791210	823	45.	29.767	.18	.13								
82	791210	905	34.	7.563	.28	.21								
83	791210	1019	158.	3.168	.41	.27								
84	791210	1116	120.	8.160	.14	.08								
85	791210	1420	139.	4.740	.16	.12								
86	800329	212	70.	5.404	.37	.20								
87	800329	221	80.	4.374	.33	.20								
88	800424	1106	321.	4.288	.16	.11								
89	800426	1947	319.	7.579	.86	.61								
90	800508	121	53.	10.890	.18	.13	5	10	0	11	0	13	270	3
91	800523	1439	103.	6.531	.14	.09	118	6	145	9	150	12	0	6
92	800529	309	4.	4.158	.32	.21	330	8	325	8	335	10	248	1
93	800601	352	337.	4.895	.18	.13	275	3	280	4	300	6	158	7
94	800601	430	93.	3.443	.16	.10	275	3	280	4	300	6	158	7
95	800602	1219	288.	4.907	.17	.13	175	13	175	12	200	9	135	11
96	800602	2151	205.	12.509	.16	.11	180	13	178	13	185	11	135	10
97	800612	2010	146.	15.918	.37	.28	110	12	135	12	180	13	293	5
98	800618	1021	276.	10.039	.16	.12	290	3	300	4	325	6	293	5
99	800619	334	262.	3.105	.18	.12	235	6	240	6	130	5	203	4
100	800619	446	249.	8.978	.14	.09	235	6	240	6	130	5	203	4

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101	800619	714	183.	8.643	.12	.08	235	6	240	6	230	5	203	4
102	800620	407	355.	9.525	.66	.35	23	9	25	11	15	13	23	3
103	800620	1924	148.	6.708	1.26	.54	55	6	48	5	50	7	45	8
104	800625	1931	16.	8.429	1.02	.36	330	4	330	4	355	7	23	2
105	800626	1522	83.	6.017	.22	.14	85	11	80	11	90	8	90	8
106	800628	1530	109.	7.467	.36	.22	85	12	85	13	85	14	90	10
107	800704	1541	105.	4.696	.57	.37	155	4	110	3	120	3	45	4
108	800704	1607	90.	3.153	1.22	.63	155	4	110	3	120	3	45	4
109	800704	1701	186.	4.250	.78	.46	155	4	110	3	120	3	45	3
110	800706	1156	193.	1.844	1.13	.84	115	3	310	1	315	3	23	1
111	800707	836	70.	4.850	.23	.17	350	2	340	2	40	2	68	3
112	800708	2351	18.	4.528	.32	.19	325	9	325	12	15	5	270	6
113	800709	33	24.	5.582	.41	.30	325	9	325	12	15	5	270	6
114	800709	40	29.	5.313	.41	.30	325	9	325	12	15	5	270	6
115	800709	109	274.	6.621	.19	.14	325	9	325	12	15	5	270	6
116	800709	128	276.	11.563	.93	.57	325	9	325	12	15	5	270	6
117	800709	143	327.	12.809	.82	.58	325	9	325	12	15	5	270	6
118	800709	205	1.	7.307	.49	.22	325	9	325	12	15	5	270	6
119	800709	357	99.	5.409	.51	.33	340	7	335	10	340	10	293	5
120	800709	416	324.	9.138	1.01	.66	340	7	335	10	340	10	293	5
121	800709	509	304.	8.766	1.26	.62	340	7	335	10	340	10	293	5
122	800709	521	332.	10.880	.60	.45	340	7	335	10	340	10	293	5
123	800709	532	288.	6.527	.53	.35	340	7	335	10	340	10	293	5
124	800709	537	303.	7.609	.74	.45	340	7	335	10	340	10	293	5
125	800709	509	294.	7.624	1.01	.66	340	7	335	10	340	10	293	5
126	800709	704	357.	5.464	.77	.46	340	7	335	10	340	10	293	5
127	800709	741	4.	3.710	1.34	1.18	340	7	335	10	340	10	293	5
128	800709	807	308.	5.338	2.34	1.42	340	7	335	10	340	10	239	5
129	800709	1114	322.	3.594	1.13	.71	330	8	325	8	335	12	293	5
130	800713	237	5.	7.891	.66	.34	15	6	15	9	5	9	315	2
131	800713	1051	11.	6.474	1.75	1.16	355	4	335	6	310	10	315	2
132	800713	1109	9.	5.492	1.30	.99	355	4	335	6	310	10	315	2
133	800713	1057	3.	4.031	1.75	1.16	355	4	335	6	310	10	315	2
134	800713	1118	0.	4.683	1.30	.99	355	4	335	6	310	10	315	2
135	800714	502	152.	2.701	.18	.13	115	4	105	2	105	4	0	1
136	800715	1216	306.	10.024	1.27	.78	338	12	340	12	0	9	338	7
137	800715	1945	340.	16.117	.95	.54	355	11	345	16	15	12	338	7
138	800716	1853	34.	7.330	.78	.68	60	4	58	4	48	4	23	7
139	800717	200	193.	5.687	.23	.16	140	12	140	12	140	12	90	8
140	800717	526	145.	3.104	.18	.13	125	7	115	8	105	8	90	8
141	800717	624	107.	6.957	.16	.11	125	7	115	8	105	8	90	8
142	800717	908	167.	5.207	.15	.13	125	7	115	8	105	8	90	8
143	800718	1659	59.	8.015	.12	.07	85	8	80	8	100	7	45	5
144	800718	1713	23.	8.957	.14	.09	85	8	80	8	100	7	45	5
145	800720	306	1.	6.818	.37	.28	28	9	18	7	20	8	338	4
146	800720	311	15.	4.447	.37	.28	28	9	18	7	20	8	338	4
147	800730	2352	254.	7.061	.45	.26	315	13	310	9	298	8	90	6
148	800803	1659	68.	20.851	.52	.27	30	6	75	10	70	11	248	2
149	800803	1714	4.	14.893	.39	.18	30	6	75	10	70	11	248	2
150	800803	1732	66.	8.602	.29	.24	30	6	75	10	70	11	248	2

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152	800805	241	94.	8.844	.49	.23	65	16	50	12	53	14	45	3
153	800805	1044	68.	18.507	.51	.18	50	16	45	18	50	19	23	9
154	800805	2217	121.	16.908	.47	.26	90	15	73	16	70	21	23	9
155	800820	638	63.	5.469	.45	.21	60	12	60	12	110	14	68	4
156	800820	953	355.	6.319	.61	.28	60	12	60	12	110	14	68	4
157	800820	1028	83.	10.356	.63	.45	90	22	90	20	90	27	23	10
158	800820	1040	122.	17.310	.16	.13	90	22	90	20	90	27	23	10
159	800820	1152	83.	16.015	.14	.09	90	22	90	20	90	27	23	10
160	800821	1317	122.	15.063	1.00	.40	100	20	110	20	105	21	23	10
161	800822	2207	197.	12.759	2.11	1.01	160	13	180	9	205	9	90	6
162	800822	2218	108.	8.099	.49	.31	160	13	180	9	205	9	90	6
163	800822	2240	123.	8.832	.69	.46	160	13	180	9	205	9	90	6
164	800823	959	130.	6.809	.86	.56	130	5	125	6	125	7	90	6
165	800823	1041	195.	5.503	1.59	1.39	130	5	125	6	125	7	135	1
166	800823	1114	133.	8.032	2.25	1.43	130	5	125	6	125	7	135	1
167	800823	1120	101.	5.180	2.25	1.43	130	5	125	6	125	7	135	1
168	800823	1137	133.	7.347	1.02	.81	130	5	125	6	125	7	135	1
169	800823	1019	168.	4.991	.49	.31	130	5	125	6	125	7	135	1
170	800823	1027	192.	4.583	.49	.31	130	5	125	6	125	7	135	1
171	800823	1045	221.	5.202	1.59	1.39	130	5	125	6	125	7	135	1
172	800824	1715	106.	3.733	.18	.12	140	2	175	4	165	6	90	6
173	800830	927	57.	11.566	.14	.11	65	6	25	10	35	11	293	6
174	800830	1343	58.	8.800	.32	.23	65	6	25	10	35	11	90	6
175	800830	1627	53.	8.705	.21	.14	70	6	50	8	40	12	68	6
176	800909	1239	23.	26.480	.22	.12	35	10	10	10	20	14	135	7
177	800909	1904	141.	10.244	.66	.30	85	12	65	13	65	16	68	5
178	800911	208	57.	12.140	.14	.10	20	21	50	17	40	19	0	9
179	800911	215	41.	15.276	.20	.14	20	21	50	17	40	19	0	9
180	800911	220	30.	21.718	.20	.14	20	21	50	17	40	19	0	9
181	800911	246	36.	10.024	.12	.09	20	21	50	17	40	19	0	9
182	800913	1020	96.	13.675	.53	.19	75	16	65	14	75	12	45	13
183	800917	1740	33.	17.283	.14	.08	88	12	55	7	30	13	0	6
184	800917	1837	60.	5.868	.19	.15	88	12	55	7	30	13	0	6
185	800917	2026	81.	9.078	.33	.19	88	12	55	7	30	13	0	6
186	800925	442	68.	6.246	.14	.13	70	10	55	12	50	14	135	4
187	800925	459	54.	15.215	.18	.13	70	10	55	12	50	14	135	4
188	800925	529	113.	11.896	.12	.09	70	10	55	12	50	14	135	4
189	801001	644	49.	20.999	.24	.16								
190	801001	924	116.	16.520	.33	.18								
191	801002	832	39.	11.493	.26	.14								
192	801002	1055	136.	19.830	.28	.12								
193	801007	700	2.	17.331	.16	.09								
194	801007	1413	15.	23.016	.40	.30								
195	801007	2105	92.	14.328	.41	.33								
196	801008	2200	6.	6.026	.25	.18								
197	801008	2210	35.	10.533	1.08	.44								
198	801020	1203	116.	6.982	.52	.25								
199	801023	110	116.	7.806	.12	.06								
200	801025	1414	173.	3.674	.12	.10								

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201	801028	48	186.	11.653	.15	.12								
202	801028	506	170.	9.871	.16	.10								
203	801028	550	152.	9.321	.16	.12								
204	801028	559	43.	4.518	.18	.12								
205	801028	634	167.	10.601	.16	.10								
206	801028	636	62.	31.075	.16	.10								
207	801029	16	41.	7.221	.88	.43								
208	801029	29	92.	10.470	.88	.43								
209	801029	210	128.	10.540	.12	.10								
210	801029	713	94.	9.291	.12	.07								
211	801029	921	115.	23.960	1.87	.63								
212	801029	1310	165.	13.899	.28	.20								
213	801029	1447	77.	8.938	.27	.14								
214	801029	1658	29.	9.479	.16	.10								
215	801112	720	73.	8.876	.12	.08								
216	801113	2228	129.	15.042	.26	.15								
217	801115	1536	91.	5.965	.27	.11								
218	801116	13	85.	5.442	.12	.09								
219	801116	2024	81.	18.791	.32	.21								
220	801118	134	13.	10.538	.18	.06								
221	801119	516	193.	7.733	.20	.11								
222	801124	2222	119.	16.872	.12	.07								
223	801124	2340	42.	8.318	.12	.07								
224	801125	2022	101.	10.218	.12	.09								
225	801125	2209	209.	9.711	.14	.09								
226	801126	108	179.	3.017	.18	.13								
227	801126	437	125.	3.639	.53	.44								
228	801126	505	7.	10.076	.25	.19								
229	801126	534	351.	8.048	.41	.29								
230	801126	712	47.	6.778	.17	.14								
231	801213	1743	341.	26.136	.12	.07								
232	801214	405	360.	11.358	.12	.07								
233	801214	429	47.	14.445	.11	.06								
234	801223	1531	145.	10.192	.12	.06								
235	801231	2020	142.	12.855	.64	.27								
236	810101	1402	127.	16.380	.16	.13								
237	810203	404	61.	4.484	.11	.07								
238	810308	2136	86.	10.132	.12	.10								
239	810324	248	29.	6.864	.14	.08								
240	810325	1424	99.	10.213	.12	.07								
241	810326	957	26.	9.913	.28	.19								
242	810326	1029	63.	12.935	.22	.10								
243	810326	1152	64.	9.069	.24	.09								
244	810326	1158	32.	12.014	.24	.09								
245	810326	1241	86.	12.291	1.28	.68								
246	810408	1900	87.	11.479	.16	.09								
247	800501	824	25.	2.537	.16	.08								
248	810501	1215	67.	13.386	.25	.14								
249	810501	1549	104.	25.830	.18	.11								
250	810503	1757	107.	6.678	.26	.13								

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252	810518	1153	6.	13.028	.14	.11								
353	810929	430	49.	12.034	.43	.38								
254	810527	1804	6.	6.264	.22	.18								
255	810527	1829	25.	12.082	.14	.11								
256	810527	2155	3.	12.690	.58	.24								
257	810528	1837	10.	9.833	.16	.11								
258	810603	1344	6.	7.760	.16	.11								
259	810603	1412	11.	9.201	.40	.21								
260	810603	1619	5.	7.207	.47	.26								
261	810604	716	33.	16.292	.18	.14								
262	810604	752	20.	4.521	.26	.22								
263	819609	235	77.	15.229	.84	.47								
264	810609	324	344.	7.332	.15	.14								
265	810609	541	35.	17.247	.14	.10								
266	810609	614	87.	15.778	.24	.17								
267	810610	1902	151.	8.318	.82	.42								
268	810612	958	167.	6.715	1.09	.41								
269	810612	1254	174.	12.382	.29	.17								
270	810612	2301	147.	16.763	.29	.17								
271	810616	1246	89.	12.024	1.16	.36								
272	810616	2134	142.	8.565	.28	.14								
273	810617	851	133.	8.483	.14	.10								
274	810617	1248	104.	9.219	.55	.31								
275	810617	1536	192.	4.572	1.76	1.28								
276	810617	1547	148.	7.289	1.76	1.28								
277	810617	1601	118.	5.344	.12	.09								
278	810617	1725	94.	4.176	1.31	.99								
279	810617	1957	168.	8.500	.56	.45								
280	810617	2149	188.	7.897	.22	.19								
281	810617	2203	155.	8.853	.22	.19								
282	810618	1525	247.	2.504	2.75	2.36								
283	810620	2107	72.	7.170	.20	.10								
284	810620	2218	45.	4.261	.20	.10								
285	810621	1544	124.	4.598	.29	.24								
286	810621	1631	279.	5.611	.76	.65								
287	810630	1051	100.	7.165	.49	.21								
288	810630	1104	86.	13.179	.22	.17								
289	810630	1109	123.	18.788	.22	.17								
290	810630	1118	96.	6.616	.22	.17								
291	810703	1608	14.	11.994	.12	.08								
292	810703	1635	66.	12.181	.23	.15								
293	810712	631	51.	15.454	.20	.09								
294	810714	1557	15.	2.772	.26	.12								
295	810715	657	42.	5.053	.29	.17								
296	810715	755	196.	5.151	.37	.17								
297	810715	2214	143.	12.700	.60	.43								
298	810716	2230	84.	8.922	.14	.11								
299	810717	29	8.	14.521	.11	.09								
300	810717	355	336.	7.722	.15	.10								

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
301	810717	415	332.	5.623	.19	.12								
302	810717	447	338.	13.055	1.09	.74								
303	810717	536	353.	6.792	.39	.26								
304	810717	626	357.	6.649	.21	.11								
305	810717	654	48.	7.688	.17	.09								
306	810717	928	53.	11.964	.62	.20								
307	810723	1945	316.	17.664	1.11	.78								
308	810725	624	258.	6.523	.21	.18								
309	810725	640	140.	6.675	.21	.18								
310	810725	707	239.	5.829	.44	.33								
311	810725	719	265.	4.786	.44	.33								
312	810725	745	256.	7.077	.12	.10								
313	810725	835	244.	16.702	.14	.09								
314	810725	1047	329.	8.722	.10	.07								
315	810725	1102	307.	12.327	.12	.07								
316	810725	1227	281.	7.996	.40	.12								
317	810725	2339	339.	13.475	.18	.15								
318	810726	11	340.	5.177	.28	.21								
319	810726	107	277.	11.675	.24	.22								
320	810730	850	25.	5.971	.23	.08								
321	810730	1301	106.	9.507	.50	.23								
322	810730	1336	126.	9.473	.26	.18								
323	810816	247	35.	9.968	.40	.19								
324	810816	339	87.	21.605	.35	.23								
325	810816	432	85.	17.024	.54	.28								
326	810816	455	72.	17.508	.49	.23								
327	810816	1557	89.	16.213	.33	.12								
328	810816	2326	163.	8.986	.89	.40								
329	810816	2336	171.	13.788	1.40	.69								
330	810816	2355	118.	29.951	.29	.20								
331	810817	26	164.	9.728	.14	.12								
332	810817	152	124.	7.717	.45	.23								
333	810817	214	131.	10.208	.90	.58								
334	810817	247	174.	8.714	.45	.18								
335	810817	304	93.	9.295	.30	.11								
336	810817	830	118.	9.289	.79	.38								
337	810818	2228	68.	11.156	1.34	.97								
338	810819	108	22.	5.868	.76	.51								
339	810820	1148	360.	8.207	.21	.14								
340	810820	2142	319.	6.758	.21	.10								
341	810820	2340	318.	3.509	.47	.36								
342	810821	0	284.	2.767	.27	.22								
343	810821	1515	157.	3.658	.45	.23								
344	810821	1658	135.	6.879	.64	.32								
345	810823	1559	135.	9.734	.88	.48								
346	810826	1350	143.	10.258	.16	.11								
347	810826	1521	179.	9.494	1.24	.45								
348	810902	1747	165.	3.015	.85	.54								
349	810914	1554	321.	11.225	1.19	.88								
350	810914	1606	290.	1.990	1.08	.67								

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
351	810920	1511	139.	6.389	.18	.13								
352	810929	406	22.	22.510	2.81	1.99								
353	810929	430	49.	12.034	.43	.38								
354	811003	1521	294.	.937	.26	.19								
355	811004	655	351.	11.070	.40	.21								
356	811004	1504	354.	8.938	.62	.35								
357	811004	1542	356.	11.323	.22	.10								
358	811004	1945	102.	19.412	.29	.21								
359	811004	2203	5.	14.677	.22	.16								
360	811004	2231	350.	16.435	.64	.46								
361	811004	2245	14.	13.308	3.19	1.31								
362	811007	646	14.	8.682	.11	.07								
363	811007	650	35.	6.620	.11	.07								
364	811007	1645	88.	18.152	1.44	.43								
365	811007	1702	86.	19.057	.83	.36								
366	811007	1720	69.	16.196	.12	.10								
367	811007	1949	147.	5.577	.33	.12								
368	811007	2041	99.	21.300	.32	.12								
369	811007	2119	136.	17.738	.48	.26								
370	811008	1809	122.	11.430	.16	.10								
371	811009	2314	315.	4.879	.18	.10								
372	811010	126	122.	8.658	.21	.15								
373	811010	203	280.	31.676	.14	.08								
374	811013	1915	114.	10.282	.35	.16								
375	811013	1934	119.	8.815	.14	.10								
376	811014	35	53.	5.725	.35	.19								
377	811018	1451	309.	5.499	.21	.10								
378	811018	1505	239.	12.749	.11	.09								
379	811020	32	35.	9.084	.11	.07								
380	811020	1530	20.	14.687	.15	.10								
381	811025	955	46.	4.830	.18	.14								
382	811029	1723	286.	6.768	.14	.09								
383	811030	1256	356.	12.873	.14	.09								
384	811031	932	352.	6.401	.14	.09								
385	811031	1114	344.	4.405	.16	.11								
386	811031	433	135.	12.941	.12	.10								
387	811102	511	130.	5.488	.11	.05								
388	811102	917	155.	17.855	.20	.09								
389	811102	1658	207.	6.594	.24	.12								
390	811104	233	61.	12.012	.21	.13								
391	811113	1259	124.	10.850	.22	.13								
392	811113	1311	123.	17.134	.22	.13								
393	811113	1645	160.	9.663	.28	.20								
394	811114	239	191.	9.083	.18	.15								
395	811120	1220	101.	18.411	.11	.08								
396	811120	1326	90.	21.922	.12	.07								
397	811120	1806	100.	24.621	.18	.11								
398	811120	2002	147.	6.493	.41	.27								
399	811120	2017	100.	23.598	.37	.25								
400	811125	911	215.	10.555	.25	.15								

